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OPEN FIRES
AND
TRANSPORT OF FIREBRANDS

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INVESTIGATION OF OPEN FIRES AND TRANSPORT OF FIREBRANDS WITHIN FIRE SYSTEMS

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covering the period

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OPEN FIRES AND TRANSPORT OF FIREBRANDS

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S U M M A R Y

The research program comprises two different problems: open fires and transport of firebrands, which will be treated separately:

Open Fires

The investigation on open fires has been directed towards the study of the basic laws governing the process, which relate the physico-chemical properties of the fuel with the observable characteristics of a fire, such as flame temperature, flame size, convection column, radiant energy, etc.

A fire is a very complex process. Its study is being conducted by carrying out a series of measurements in a research facility and by studying theoretically some partial processes which are part of the over-all process.

A research facility has been prepared in a tower of a test stand for aircraft engines which has been conditioned to that purpose. The research facility comprises several cylindrical open vessels (burners) of different diameters, for studying the fires produced by several types of fuels. The fuel is kept at a constant level in the burners and the fuel consumption is measured by means of a constant-pressure volumetric system. Thermocouples and pressure probes are placed in and around the fire to measure temperatures and velocities of the gases.

Burning rates, flame temperatures, flame sizes, fuel temperatures, gas velocities, etc, are being measured for gasoline, kerosene and for dioxane-water mixtures. The dioxane is a fuel which mixes with water in all proportions and it has a similar boiling temperature than that of the water. Therefore, dioxane-water mixtures keep a constant composition during combustion and by varying the amount of water of the mixture it is possible to change in a continuous form the properties of the fire.

Some theoretical problems in connection with open fires are also being studied, such as motion and mixing of a hot gas stream with air and diffusion flames considering body forces.

All experimental and theoretical studies are progressing satisfactorily and several results are given in the paper.

Transport of Firebrands

The research work on transport of firebrands is

well advanced. The experimental work consists in the attainment of lifetimes and laws of variation of weight and aerodynamic drag of burning particles as functions of time. The theoretical work consists in the calculation of the flight paths of firebrands under given wind conditions (horizontal and vertical) utilizing the abovementioned experimental data.

Two research facilities have been designed and constructed. A small aspiration wind tunnel is presently being used for measuring lifetimes, weights and aerodynamic drags of firebrands at different air speeds. At present, a balance (scale) is being used for such measurements, but a two component strain-gauges balance and a recording system will be shortly installed.

A rotary arms research facility has also beingconstructed and it will be soon utilized for large firebrands.

The theoretical treatment of the problem has been already solved, and the differential equations of the process have been integrated through an approximated method.

Parameters of the process are: firebrand initial shape, firebrand size, kind of wood and moisture content. The investigation has been initiated with spherical firebrands, which correspondsto an extreme case (poor flight conditions but long lifetimes) and with pine tree wood (pinus pinaster) for several diameters and for different moisture contents. Flight paths, maximum horizontal distance reached by a firebrand, maximum heights, etc. have already been obtained and several data are given in the paper. It may be pointed out that all fundamental work on the firebrand problem has already been done, although a very large amount of work remain to be done due to the very large number of parameters of the process, specially firebrand shapes, kind of wood and wind conditions.

1. INTRODUCTION

The research program comprises two very different problems: Open Fires and Transport of Firebrands. The first problem is very complex, specially because the investigation has been directed towards the attainment of the fundamental laws governing the process. Transport of firebrands, consisting in the study of lifetimes and flight paths of burning particles, is a problem of simpler nature.

The research work was planned in different form for the two problems. Owing to the complex nature of the process of an open fire, which is the resultant of several other partial processes of different nature, it is necessary to perform several studies on such partial processes before attempting the study of the over-all process.

The research work corresponding to that part of the program was devoted to such studies, as well as to the design of suitable research facilities. All these works are progressing satisfactorily and the research facilities have already been constructed.

The research work on transport of firebrands is well advanced. The experimental work on this problem consists in the attainment of lifetimes and laws of variation of weight and aerodynamic drag of burning particles as functions of time. Parameters of the process are firebrand initial shape, kind of wood, moisture content and wind speed. The theoretical work consists in the calculation of the flight paths of firebrands, under given wind conditions (horizontal and vertical), using the abovementioned experimental data.

All the fundamental work on transport of firebrands has already been done. The research facilities have been designed and constructed and the theory of the problem is well established. Flight paths and lifetimes of several types of firebrands have already been determined.

I - INVESTIGATION OF OPEN FIRES

2. RESEARCH PROGRAM

The research program on open fires consists in the study of axi-symmetrical fires produced by burning liquid fuels contained in cylindrical vessels (burners) in the open atmosphere.

The fundamental objective of the investigation is the attainment of the laws relating the physico-chemical properties of the fuel with the characteristics of the fire, such as burning rate, temperature, size and emissivity of the flame, flow field around the fire and characteristics of the convection column.

The study of the several processes which compose an
is
open fire presently being performed. Therefore, only some partial results will be given in the paper. The explanations will be directed mainly to the analysis of the problems and to the form in which they are being studied.

The complex process of an open fire of this kind may be described as follows (Fig.1):

The fuel is warmed up and partially vaporized by the heat transmitted from the flame. Fuel vapors are carried into the flame by means of diffusion and convection, and the air is drawn into and along the flame due to free convection. Part of its oxygen diffuses into the flame and reacts there, and the hot combustion products and air in excess move upwards forming the convection column.

If the flame is large enough, the process is turbulent and diffusion is primarily of a macroscopic type. Thermal energy of the fuel is consumed in three main ways: radiant heat transfer from the flame to its surroundings, production of a hot column of convection gases moving at a certain speed, and heat transferred from the flame to the fuel. This last heat transfer is used in warming up and in vaporizing the fuel, balancing finally the process.

The over-all process of a fire cannot be studied theoreticaly due to its complexity, and lack of knowledge on some of their partial processes, as fluid motion with body forces, or turbulent flames, of which only rudimentary solutions exist. Therefore, a large part of the research work will have to be conducted experimentally.

The main independent variables of the process are: burner diameter and fuel properties, specially the heat of combustion and the latent heat of evaporation.

On the other hand, the principal dependent variables to be determined are:

a) Flame temperature

b) Flame emissivity

c) Flame size

d) Combustion efficiency

e) Burning rate

f) Heat balance

g) Velocity and temperature of the convection column.

Flame temperature

In open fires the flames are of the diffusion type. Therefore, maximum local values of the flame temperature should be close to the adiabatic combustion temperature. There are some data on the values of flame temperatures in open fires [1], which are considerably smaller than those corresponding to the adiabatic combustion temperature. These experimental data were obtained by means of optical measurements, which give mean values through the flame thickness, where temperature changes sharply in these types of flames. Furthermore, turbulenced may influence such mean values, because it influences the process and because it also introduces an average time value of the temperature.

These mean values are the interesting ones, rather than the peak values, because thermal radiation depends on them. However, it is important to know the relationship existing between them.

There is no information on the possible dependency of flame temperature with fire size, and this is one of the subjects which will be investigated. An optical equipment will be acquired for measuring flame temperatures by means of the reversal method and by using two colors pyrometry. In the meantime, thermocouples are being used.

Flame emissivity

Flame emissivity depends, essentially, on the existence of soot particles and, therefore, it cannot be easily calculated. Emissivities will be measured by means of two colors pyrometry and with total radiation thermopiles, which have been already ordered.

Flame size

A theoretical model for the calculation of the length of a turbulent flame with free convection does not appear feasible. Flame lengths will then be determined experimentally by means of photographs. Their laws of variation as function of burner size and as function of fuel characteristics are presently being obtained for gasoline, kerosene and for several dioxane-water mixtures.

Combustion efficiency

Combustion efficiency accounts for the unburnt fuel and combustible products (CO) which exist in the stack gases. It may be measured by the heat of combustion of the stack gases as compared with the heat of reaction of the fuel.

Analysis of stack gases has been postponed until a chromatography equipment, recently acquired by the Institute, be ready for the analysis.

Burning rates

Burning rates (grams of fuel consumed per unit time) are being measured for gasoline, kerosene and dioxane-water mixtures with the research facilities described in paragraph 3.

Burning rates may be calculated as well as their laws of variation with burner sizes and fuel properties once the flame characteristics are known (average temperature, emissivity and size). For large flames almost all heat is transferred from the flame to the fuel through radiation, which can be calculated from the abovementioned data.

By taking a conical shape for the flames, the geometrical factor of radiant heat exchange flame-burner is presently being calculated as a function of flame length. Once this geometrical factor is known, from the values of flame emissivity and flame tamperature, the radiant heat reaching the fuel surface may be readily determined.

Neglecting the reflectivity of the fuel surface, the radiant heat reaching the fuel surface is partially used in vaporizing the fuel; some percentage of it is utilized in heating up the fuel, and a very small percentage of it is transmitted through the fuel to its surroundings. This heat distribution is determined by measuring the temperature profiles within the fuel, or else, it can be calculated quite accurately. Burning rates result from that heat balance.

In Figs. 2 and 3 some examples of burning rates and temperature distributions are shown.

Heat balance

A simple model for the energy balance of on open fire is given by the expression (Fig.1):

$$\dot{m}\ \eta_q\, q_r = \dot{M}\left[\bar{c}_p\ (T_c - T_\infty) + \frac{\bar{V}_c^2}{2}\right] + Q_{F\infty} + Q_{Ff} \qquad (1)$$

in which $\dot{m}\ \eta_q\ q_r$ is the heat released by chemical reaction ($\dot{m}$ = burning rate, η_q = combustion efficiency and q_r = heat of combustion); $\dot{M}\left[\bar{c}_p\ (\bar{T}_c - T_\infty) + \frac{\bar{V}_c^2}{2}\right]$ is the increasement of stagnation enthalpy in the convection column ($\dot{M}$ = mass flow in the convection column, $\bar{T}_c$ = average temperature and $\bar{V}_c$ = average speed); $Q_{F\infty}$ is the radiant heat exchange between the fire and its surrounding, and Q_{Ff} is the radiant heat transferred from flame to the fuel.

The value of Q_{Ff} can be calculated according to the preceding paragraph. Q_{Ff} will be measured by means of thermopiles and it can also be calculated from the data of flame temperature, size, and emissivity. Therefore, equation (1) gives the amount of energy imparted to the convection column, and from these data it is expected to calculate approximately convection column speeds. However, convection column temperatures and velocities will also be measured with the research facilities discussed in paragraph 3.

Convection columns

Two basic problems are being studied in connection with convection columns.

Motion and mixing including body forces of a hot gas stream in open air is being studied by means of an integral method similar to that used in boundary layer theory. This method does not hold for the initial stages of the mixing which are being studied through a perturbation method.

As a part of this program diffusion flames considering body forces are being studied.

3. RESEARCH FACILITIES

(K) [A research facility was prepared for studying open fires, which is represented in Fig. ~~1~~ 12

The burner is a cylindrical open vessel in which the fuel is kept at a constant level by means of a small tank, where the fuel level is mantained with a ~~float and needle system and a~~ small overflow tube placed in the center of the vessel.

Fuel is supplied from a tank and fuel consumption is measured by means of a constant pressure volumetric system.

Several types of vessels were tested until a model was finally selected. This vessel is represented in Fig.13 and it has been constructed in several sizes.

Fuel depth was chosen as a compromise between opposite conditions. Large amounts of fuel in the vessel make difficult the attainment of stationary conditions, because burning rates keep increasing for very long time. On the other hand, small depths of fuel may originate important temperature gradients within the fuel, parallel to the fuel surface.

Fuel temperature is measured by means of three thermocouples which can be set at different distances from the fuel surface. The heat flux transmitted from the liquid fuel may be determined by measuring the increment of the temperature of the cooling water which surrounds the fuel container; or else, the water may be emptied in order to have a thermal insulation of air around the fuel.

Vessels of 12.5, 25 and 50 cm in diameter have ~~already~~ been constructed, ~~and vessels of 50 and 100 cm will shortly be constructed~~. All of them have very narrow rims in order to minimize heat transfer from the flame to the fuel through the vessels.

Around and above the vessel a steel frame was constructed where thermocouples and pressure probes can be fixed. Static and stagnation pressures are measured with Förthmann and Kiel probes by using micromanometers.

M At first, the research facility was placed in an engine test stand, but there were some slight air drafts which produced undesirable motion of the flame, difficulting considerably the measurements.

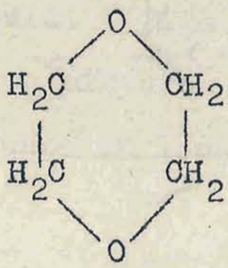
Therefore, a tower of an engine test stand was specially conditioned for the study of open fires. By means of a brick wall and a steel screen, the tower was isolated; and a roof with lateral holes was also constructed. A diagram of the tower is shown in Fig. ~~6~~ 14 ~~and a photograph of the observation window and control panel is shown in Fig.17.~~]

4. <u>FUELS</u>

N [Several types of fuel are used for studying open fires. The purpose of using different fuels is to study the influence on the process of parameters such as heat of combustion, heat of evaporation, flame luminosity (soot formation) etc. Gasoline, kerosene and ~~ethyl alcohol~~ n-heptane have ~~already~~ been tested. ~~and several other fuels will be utilized.~~

It was very desirable to have a fuel in which its properties could change in a continuous form, specially its heat of combustion, because it would enable to produce a continous variation of flame temperature. Therefore, a fuel was sought which could mix with water in all proportions, but not forming and azeotropic mixture (constant boiling temperature mixture). It was also required that the boiling point of the fuel was approximately equal to that of the water, in order that the mixture would keep the same composition during its evaporation for combustion.

Only a commercial product fulfilling such requirements was found: the ethylene-dioxide (dioxane) $C_4H_8O_2$ or:



It has a boiling temperature of 101°C and a density of

1,033 at 20ºC.

The fuel is expensive (about 90 pesetas a kilogram), but it offers special advantages for several types of studies.

In the first place, mixtures of 25 per cent water and 50% dioxane were burned and analyzed at different times. It was found that the initial proportion dioxane-water was mantained practically constant during combustion.

The heat of combustion of the dioxane was not found in the literature. Therefore it was determined at the Chemistry Laboratory of the Institute giving the following values:

100/100 Dioxane, q_r = 6,260 cal/gr.

Dioxane + 25% water in volume, q_r = 4,720 cal/gr.

Dioxane + 50% water in volume, q_r = 3,110 cal/gr.

no ~~From the values of the heat of combustion, the temperatures and equilibrium compositions of stoichiometric mixtures with air at ambient pressure are being calculated. These calculations are being performed for the three mixtures (0 , 25% , 50% of water);as such temperatures are needed for comparing these maximum (peak) possible values with the average experimental values measured in the flames.~~

Fig. 16 shows the values of q_e, q_r, and q_r/q_e for several mixtures dioxane - water.

no ~~Burning rates for dioxane mixtures have already been determined in a vessel of 30 cm in diameter, as well as temperature profiles within the liquid. (Figs. 8 and 9).~~ Fotographs of flames produced by the three mixtures in a vessel of 30cm in diameter are shown in Fig. ~~10~~ 17. It may be observed the difference in length and luminosity of the three flames.

II. TRANSPORT OF FIREBRANDS

5. ANALYSIS OF THE PROBLEM

The two-dimensional motion of a particle of mass m (the firebrand), which moves at the absolute velocity $\vec{V}(x\,y\,t)$, within a wind of velocity $\vec{u}(x\,y\,t)$ is given by the following system of differential equations (x horizontal axis, y vertical axis):

$$m \frac{d V_x}{dt} = \frac{1}{2} C_D A \rho w^2 \frac{w_x}{w} = C_D A \frac{1}{2} \rho w \; w_x \qquad (2)$$

$$m \frac{dV_y}{dt} = \frac{1}{2} C_D A \rho w^2 \frac{w_y}{w} - mg = \frac{1}{2} C_D A \rho w \; w_y - mg \qquad (3)$$

In these equations $\vec{w}$ is the relative velocity of the wind with respect to the particle, $w = |\vec{w}|$, and

$$\vec{f} = \frac{1}{2} C_D A \rho w \; \vec{w} \qquad (4)$$

is the aerodynamic force exerted on the particle, which acts in the direction of the relative velocity $\vec{w}$ of the particle, and mg is the weight. C_D is the aerodynamic drag coefficient, A is the area of the maximum cross section of the particle and ρ is the air density.

For given wind conditions, i.e. for a known function $\vec{u}(x\,y\,t)$ and if the air density function $\rho(x\,y\,t)$ is also given, system (2), (3) can be integrated, once the values of the burning particle mass m, area A and aerodynamic drag coefficient are known as functions of the relative velocity $\vec{w}$ and time t.

The functions:

$$n = \varphi(w, t)$$
$$A = \psi(w, t) \qquad (5)$$
$$C_D = \xi(w, t)$$

have to be determined experimentally by burning wood particles within an air stream of velocity w and measuring the mass m, aerodynamic drag coefficient C_D and area A as functions of time.

6. RESEARCH FACILITIES

The range of air velocities in the research facility had to be comprised from very small velocities (a few cm/sec) up to velocities of the order of the limit velocity of a wood particle in a free fall through the atmosphere. These limit velocities depend considerably on the weight and shape of the particle. For the sphere, which is a body-shape giving a maximum value for the limit velocity in a free fall (*), such velocities are of the order of 15 m/sec for spheres of wood of about 15 mm in diameter and for an air density corresponding to its standard value at sea level.

For such range of air velocities, and taking into account that very small values of the air velocities would have to be utilized, it was considered the best solution, for small particles, to use a small aspiration wind tunnel, of which some parts were already available. The tunnel was designed and constructed, and it is shown in Fig.11.

In this tunnel the air is aspirated by means of a small centrifugal blower; and a very good control of the air velocity

(*) In a free fall, a particle of wood takes the position of maximum drag, which is the position of maximum stability.

at the testing section is achieved by means of a throttle and two air intakes placed close to the blower, whose area may be varied.

Air pressure is measured by means of a micromanometer at the throat section of a Venturi disposed close to the testing section. The area of that throat is 1/4 of the area of the testing section and with this arrangement air velocities as small as 20 cm/sec may be measured.

Aerodynamic drag and weight of the particle will be measured with a two-components strain-gauges balance and a very sensitive pen recorder (micrograph). The micrograph has not yet been received, and in the meantime an ordinary balance is being used, as it is shown in the figure.

For testing large firebrands, a rotary arms facility was considered the best solution. The firebrands are placed at the tip of a long arm which rotates at low speed, driven through a worm gear by a D.C. electric motor. (Figs. 12 and 13). Aerodynamic drag of the arms are avoided by disposing fairings; and the weight and aerodynamic drag of the firebrand are measured by means of a two components strain-gauges balance. Signals from the strain-gauges are transmitted through copper rings and silver brushes to the same pen recorder (micrograph), which will also be used for the small aspiration wind tunnel.

In a research facility of this kind very small and very steady air velocities acting on the particles may be obtained, and the range of circunferential speeds of the rotary tubes is from almost 0 up to 20 m/sec.

7. EXPERIMENTAL RESULTS

Aside of the air speed, four parameters can be selected for testing burning wood particles: particle shape, particle size, kind of wood, and moisture content.

In the first part of the investigation particles, or pieces of wood, with definite geometrical shapes will be tested, such as spheres, cylinders, rectangular plates, etc. in order to make easier the analytical study of the transport of firebrands. Afterwards, natural pieces of wood (twigs) as well as pieces of bark, bracts from pine cones, acorns, etc. will be tested.

Spherical shapes were selected in the first place. This shape is not common in natural firebrands, but it was selected because it is an extreme case in which the aerodynamic limit speed is maximum but at the same time the burning time or life time of the particle is also a maximum.

Spheres from very small diameter up to values of the order of 20 mm. are being tested.

Until now, only pinus pinaster wood has been utilized. Several kinds of woods will be tested and, when possible, american species. Two values of the moisture content have so far been selected: a large value (25%) and a very small value (2%).

The research program using spherical firebrands is not yet finished, but a great number of results have already been obtained by utilizing the small wind tunnel.

Some of these results will be shown, pointing out the more significant facts about them.

Firebrands weight

Examples of typical laws of variation of particle weight as a function of time are shown in Figs. 14 , 15 and 16.

In Fig.14 the initial diameter of the spheres has been taken as a parameter. The curves have been obtained for a small value of the air velocity. It may be seen that, for low speeds, there are two well definite combustion regimes. Branch AB of the curve corresponds to flaming and in this regime the weight decreases rapidly with time. At a certain time B the flame disappears and it starts a longer period, BC ,of glowing in which the sphere weight decreases slowly.

For very low air speeds the flame surrounds the sphere. For low or medium values of the air speed the flame is of the wake type*, that is, it only takes place at the downstream side of the sphere, and for large velocities there is no flaming, although there is a combustion of the glowing type if the sphere is at first partially burned by means of a pilot flame. The time during which such pilot flame is mantained (which will be called ignition time) may be arbitrary. However, this ignition time has been fixed as the time which produces longer lifetimes once the pilot flame is removed.

Fig.15 shows the influence of air speed. For large w values only a combustion regime exists (glowing),but with considerably higher burning rates than those obtained for the glowing period at low speeds.

Finally, Fig.16 shows the influence of moisture content. It may be seen that it exerts, at low speeds, little influence on the process.

Firebrand drag

A series of experiments were carried out in order to determine the possible effect of the flame on the drag coefficient

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* Transition from one type of flame to the other depends, essentially, on the Reynolds number.

of the sphere. As a result of these experiments it was found that the influence of the flame on the drag coefficient could be neglected. Figure 17 shows the drag coefficient of a typical sphere as obtained from the experiments. We could also plot C_D as a function of the Reynolds number of the sphere. In the region of interest, C_D may be taken as constant equal to 0.47.

In fig. 18, the measured drag of a burning particle as well as its diameter, obtained by making photographs of the particle, are shown as a function of time. Fig. 19, in turn, shows two photographs of a burning particle in the flaming and glowing periods.

8. FLIGHT PATHS

From the experimental data of the preceding paragraph the flight paths and lifetimes along the trajectories can be calculated for given wind conditions.

Through relation:

$$\vec{V} = \vec{u} - \vec{w} \tag{6}$$

equations (2) and (3) are transformed into the system:

$$\frac{dw_x}{dt} + \frac{\rho C_D A}{2m} w\, w_x = \frac{du_x}{dt} \tag{7}$$

$$\frac{dw_y}{dt} + \frac{\rho C_D A}{2m} w\, w_y = g + \frac{du_y}{dt} \tag{8}$$

This system of differential equations is not linear and its solution is complicated. Numerical solutions are feasible through Adams method starting from given initial conditions and with the experimental values of $C_D (w, t)$, $A (w, t)$ and $m (w, t)$. These numerical solutions will be obtained and results will be compared to those obtained by means of the approximated analytical method which is described in the next paragraph.

Approximated analytical method

Taking a mean experimental value of parameter,

$$\boxed{\alpha = \frac{\rho\, c_D\, A}{2m}} = \text{constant} , \qquad (9)$$

an approximate solution of the problem is obtained.

Let assume that wind conditions are those shown in Fig. 20. These conditions correspond to a constant vertical component of the wind over a certain area (convection zone) superposed to a constant speed horizontal wind.

Therefore, we have:

$$u_x = \text{constant}$$

$$u_y = \text{constant} > 0 \quad \text{for} \quad x \leq L + y \frac{u_x}{u_y} \qquad (10)$$

$$u_y = 0 \quad \text{for} \quad x > L + y \frac{u_x}{u_y}$$

Equations (7) and (8) are now as follows:

$w_y = \sqrt{\frac{g}{\alpha}}$

$$\frac{dw_x}{dt} + \alpha\, w\, w_x = 0 \qquad (11)$$

$$\frac{dw_y}{dt} + \alpha\, w\, w_y = g \qquad (12)$$

By means of the following change of variable:

$$z = \frac{w_y}{w_x} \qquad (13)$$

it resuls:

$$w_x \frac{dz}{dt} = g \qquad (14)$$

$\alpha = f(\alpha)$

$$\frac{d^2z}{dt^2} = \alpha g \frac{|w_x|}{w_x} \sqrt{1 + z^2} \tag{15}$$

$2\left(1 + \frac{1}{2z^2}\right)$

The integration of eq. 15 gives:

$$\left(\frac{dz}{dt}\right)^2 = \alpha g \frac{|w_x|}{w_x} \left[\Phi(z) + C\right] \tag{16}$$

where:

$$\Phi(z) = z\sqrt{1 + z^2} + \ln\left(z + \sqrt{1 + z^2}\right) \tag{17}$$

The constant C is obtained through eq. 14, which takes the form:

$$\left(\frac{g}{w_x}\right)^2 = \alpha g \frac{|w_x|}{w_x} \left[\Phi(z) + C\right] \tag{18}$$

Eq. 16 is integrated again, thus obtaining:

$$t = \left[\alpha g \frac{|w_x|}{w_x}\right]^{-\frac{1}{2}} \Psi_1(z, C) \tag{19}$$

in which $\Psi_1(z, C)$ is:

$$\Psi_1(z, C) = \int_{z_0}^{z} \frac{dz}{\left[\Phi(z) + C\right]^{\frac{1}{2}}} \tag{20}$$

Once the function $t = f(z)$ has been obtained, the flight path of a particle is obtained as follows:

$$dx = u_x dt - w_x dt = u_x dt - \frac{1}{\alpha} \frac{w_x}{|w_x|} \frac{dz}{\Phi(z) + C} \tag{21}$$

$$dy = u_y dt - w_y dt = u_y dt - \frac{1}{\alpha} \frac{w_x}{|w_x|} \frac{z\,dz}{\Phi(z) + C} \tag{22}$$

The integration of these equations gives:

$$x - x_o = u_x\, t - \frac{1}{\alpha}\ \frac{w_x}{|w_x|}\ \psi_2\,(z\,,C) \qquad (23)$$

$$y - y_o = u_y\, t - \frac{1}{\alpha}\ \frac{w_x}{|w_x|}\ \psi_3\,(z\,,C) \qquad (24)$$

where:

$$\psi_2\,(z\,,C) = \int_{z_o}^{z} \frac{dz}{\phi(z) + C} \qquad (25)$$

$$\psi_3\,(z\,,C) = \int_{z_o}^{z} \frac{z\,dz}{\phi(z) + C} \qquad (26)$$

Boundary conditions are as follows:

$$t = 0 \quad \begin{cases} z = z_o = \dfrac{u_y - V_{yo}}{u_x - V_{xo}} \\ x = x_o \\ y = y_o \end{cases} \qquad (27)$$

Equations (19), (23) and (24) with boundary conditions (27) give the solution of the problem.

Several numerical applications have been performed, and an example is shown in Figs. 21 and 22.

The main conclusion of these calculations is that for normal values of the parameter α the relative velocity component w_y tends rapidly towards its asymptotic limiting value:

$$\left[w_y\right]_{limit} = \sqrt{\frac{g}{\alpha}} \qquad (28)$$

Also, w_x tends rapidly towards zero, and therefore, the variable z takes rapidly a very large value.

This permits a further approximation in the solution of the problem. The series expansion of function $\Phi(z) + C$ gives:

$$\Phi(z) + C = z^2\left(1 + \frac{1}{2\,z^2} + \dots\right) + \ln z + \ln\left(2 + \frac{1}{2\,z^2} + \dots\right) + C$$

Considering the very large value of z^2, we may write:

$$\Phi(z) + C \approx z^2 \tag{30}$$

Equations (20), (25) and (26) give:

$$\Psi_1(z, C) = \Psi_3(z, C) = \ln \frac{z}{z_o} \tag{31}$$

$$\Psi_2(z, C) = \frac{1}{z_o} - \frac{1}{z}\ , \tag{32}$$

and equation (18) gives:

$$w_y = \left[w_1\right]_{limit} = \sqrt{\frac{g}{\alpha}} \tag{33}$$

Introducing (31) and (32) into (23) and (24) it results for the flight path:

$$x - x_o = u_x t - \frac{u_x}{\sqrt{\alpha g}}\left[1 - \exp.\left(-\sqrt{\alpha g}\,t\right)\right] \tag{34}$$

$$y - y_o = \left(u_y - \sqrt{\frac{g}{\alpha}}\right)t \tag{35}$$

In Fig.23 several examples of flight paths are represented obtained through this approximate method.

The following significant values are easily obtained from the above written equations:

Maximum height of the flight path, which is the point at which the firebrand leaves the convection column, is given by:

$$y_{max} = y_o + \left(u_y - \sqrt{\frac{g}{\alpha}}\right) t_c \qquad (36)$$

in which t_c is the climbing time given by:

$$\exp\left(-\sqrt{ag}\, t_c\right) + \frac{g}{u_y} t_c = \frac{L}{u_x}\sqrt{ag} \qquad (37)$$

Maximum reach and total flight time

The maximum distance reached by a firebrand is given by:

$$x_{max} = u_x t_{tf} - \frac{u_x}{\sqrt{\alpha g}}\left[1 - \exp\left(-\sqrt{\alpha g}\, t_{tf}\right)\right] \qquad (38)$$

in which t_{tf} is total flight time given by:

$$\exp\left(-\frac{g}{u_y} t_{tf}\right) + g\,\frac{\sqrt{g/\alpha}}{u_y^{\,2}}\, t_{tf} = \frac{L\sqrt{\alpha g}}{u_x} + 1 \qquad (39)$$

Typical values of y_{max}, x_{max} and t_{tf} are given in Figs. 24 and 25.

Total flight times t_{tf} have to be compared with burning times (lifetimes), because the only dangerous firebrands are those reaching the ground when they are still burning.

Lifetimes are deduced from the experimental data considering the relative velocities along the flight path. However, as seen from the above solution, little error is introduced by computing such time by assuming that the firebrand is always flying at its vertical limit velocity and with a horizontal velocity equal to that of the wind.

A methodical series of experiments and studies are being performed with spherical firebrands for determining the most dangerous firebrands and wind conditions, that is to say, conditions for which the horizontal distance reached by a burning firebrand is a maximum. It is also intended to study the influence of the air temperature on the burning time of firebrands.

These studies will be repeated with different kind of wood and results will be published in a future Report.

Madrid, June, 1962.

Carlos Sánchez Tarifa
Principal Investigator

Rafael Calvo Rodés
General Director of the Institute

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2.- Fons, W. L., Bruce, M. D., Pong, W. Y. and Richards, S.S. "Summary Progress Report Forest Service. U.S. Department of Agriculture, May 31, 1960.

3.- Fons, W.L.: "Rate of Combustion from Free Surfaces of Liquid Hydrocarbons". Combustion and Flame, September, 1961.

= = = = = = = = = =

N O T A T I O N

A	Area of maximum cross section
C	Constant appearing in (17)
C_D	Drag coefficient, defined in (4)
c_p	Mean constant pressure specific heat
g	Gravitational constant
L	Width of the convection column
$\mathring{M}$	Mass flow rate in the convection column
$\mathring{m}$	Fuel burning rate
m	Firebrand mass
Q_{Ff}	Radiant heat exchange flame to fuel
$Q_{F\infty}$	Radiant heat exchange flame to surroundings
q_r	Fuel heat of combustion
T_c	Average temperature in the convection column
T_∞	Ambient temperature
t	Time
t_c	Climbing time corresponding to y_{max}
t_{tf}	Total flight time
$\vec{u}$	Wind velocity
$\vec{V}$	Firebrand absolute velocity
$\vec{w}$	Wind relative velocity with respect to the firebrand
x	Horizontal coordinate
x_{max}	Maximum distance reached by the firebrand
y	Vertical coordinate
y_{max}	Height at which the firebrand leaves the convection column; approximately, maximum height of the flight path.
z	Defined by relation (13)
α	Dimensional parameter defined by (9)

η_q Combustion efficiency

ρ Air density

Φ Defined by (17)

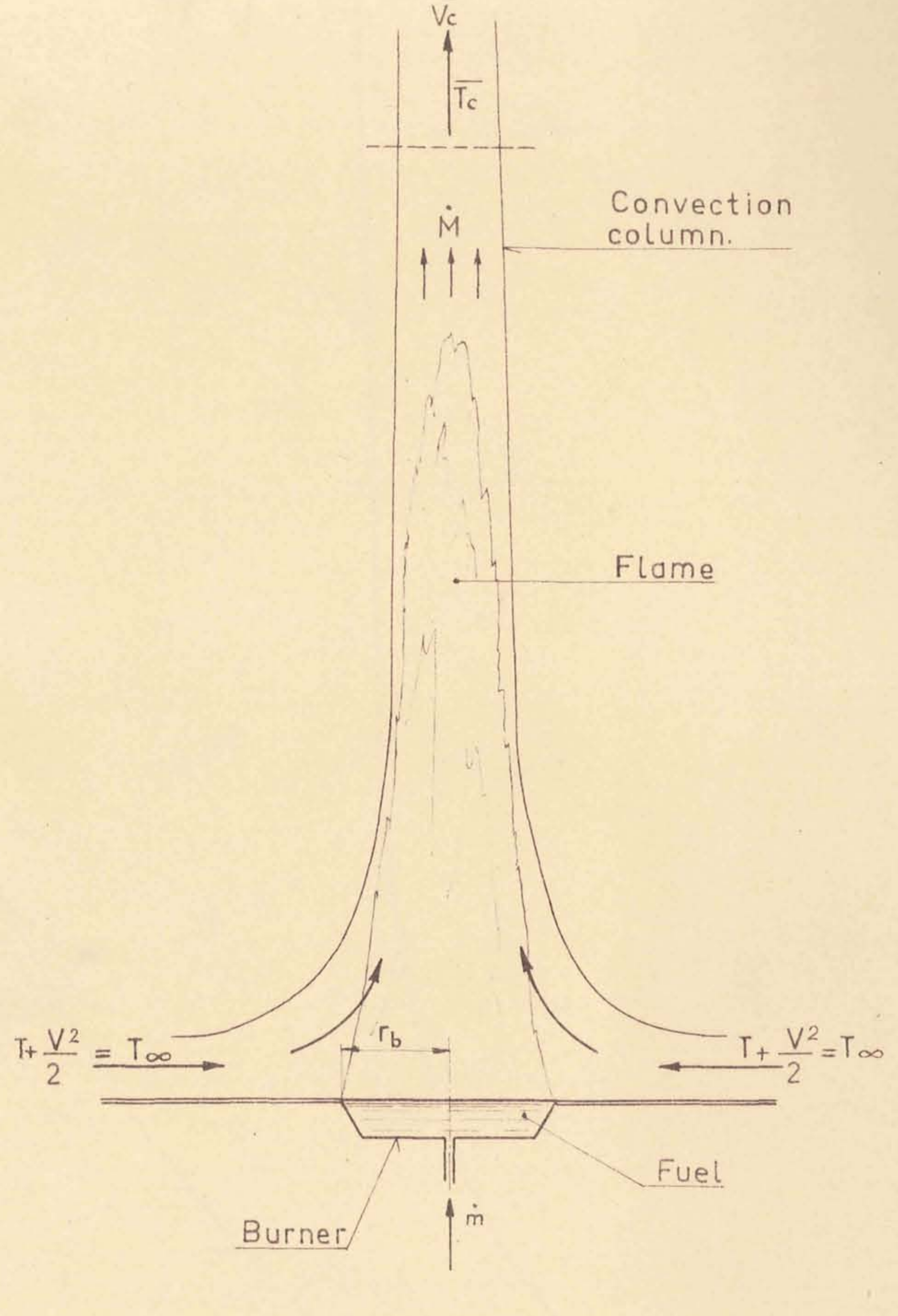
Subscripts

o Indicates initial values

x , y Indicate x and y axis direction.

= = = = = = = =

FIG. 1



SCHEMATIC MODEL OF AN OPEN FIRE

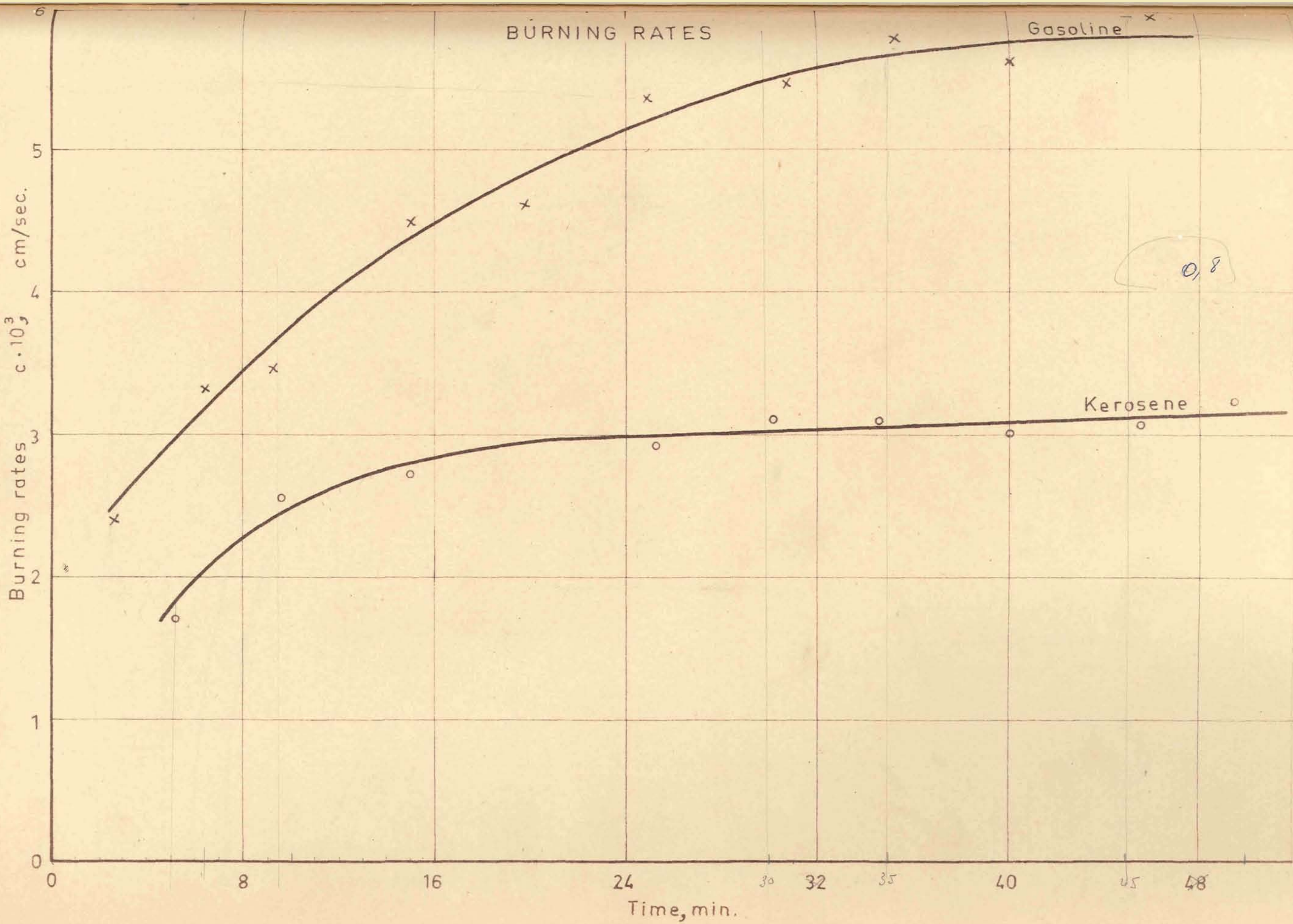

BURNING RATES
Gasoline
Kerosene
0,8
Burning rates c · 10³, cm/sec.
Time, min.
0
1
2
3
4
5
6
0
8
16
24
30
32
35
40
45
48

FIG. 2

FUEL TEMPERATURE DISTRIBUTION

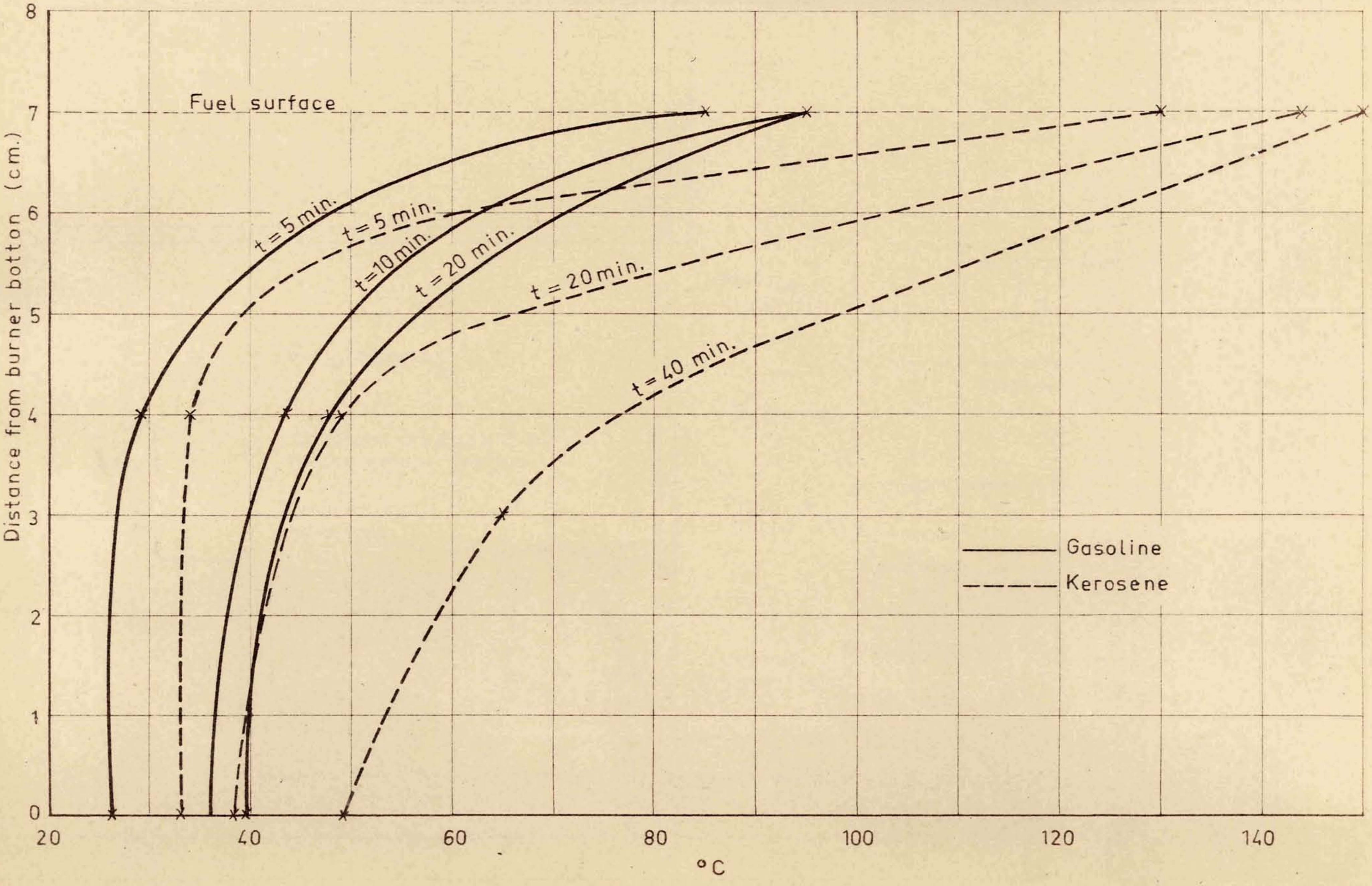


FIG. 3

SCHEMATIC DIAGRAM OF THE RESEARCH FACILITY FOR STUDYING OPEN FIRES

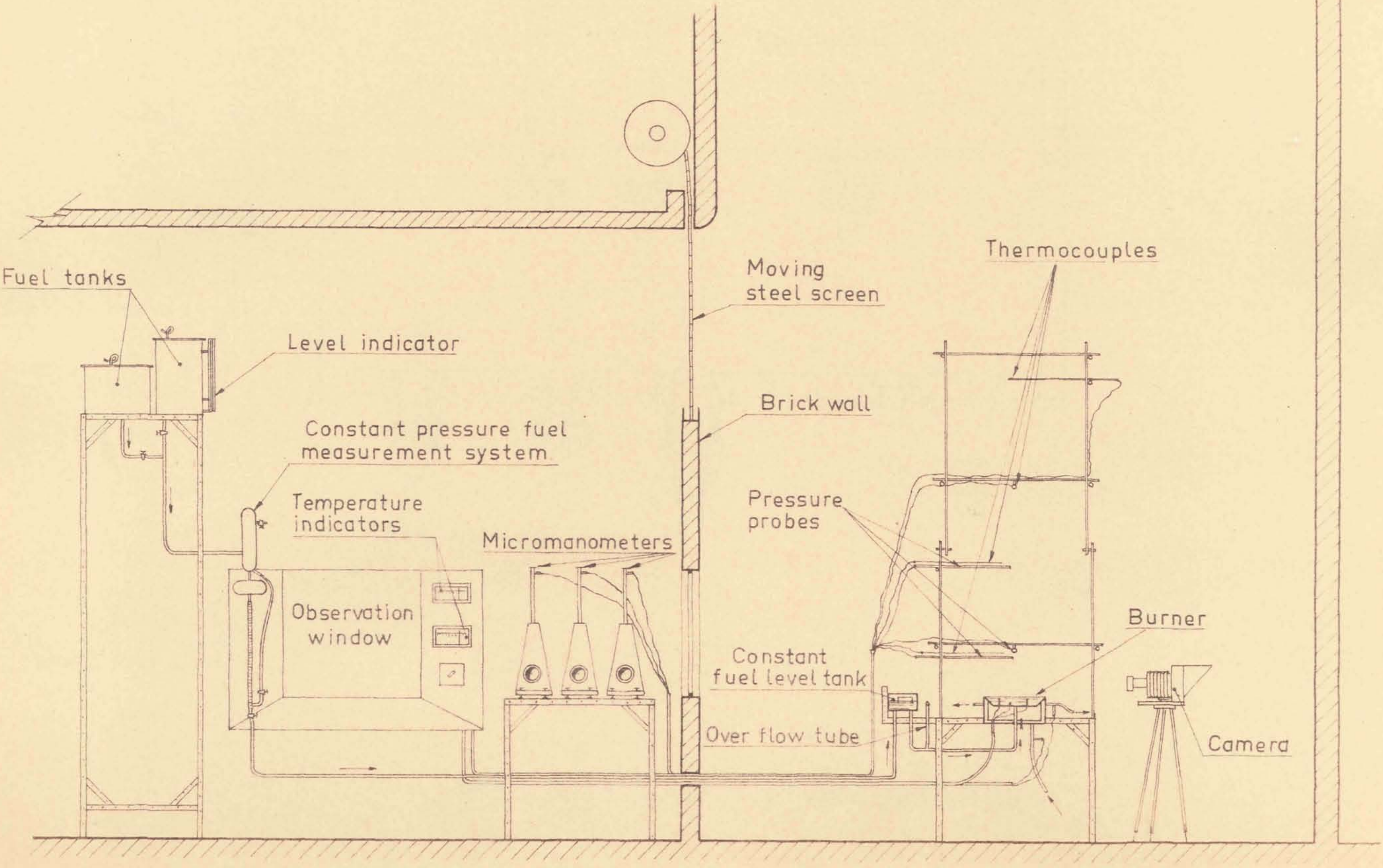
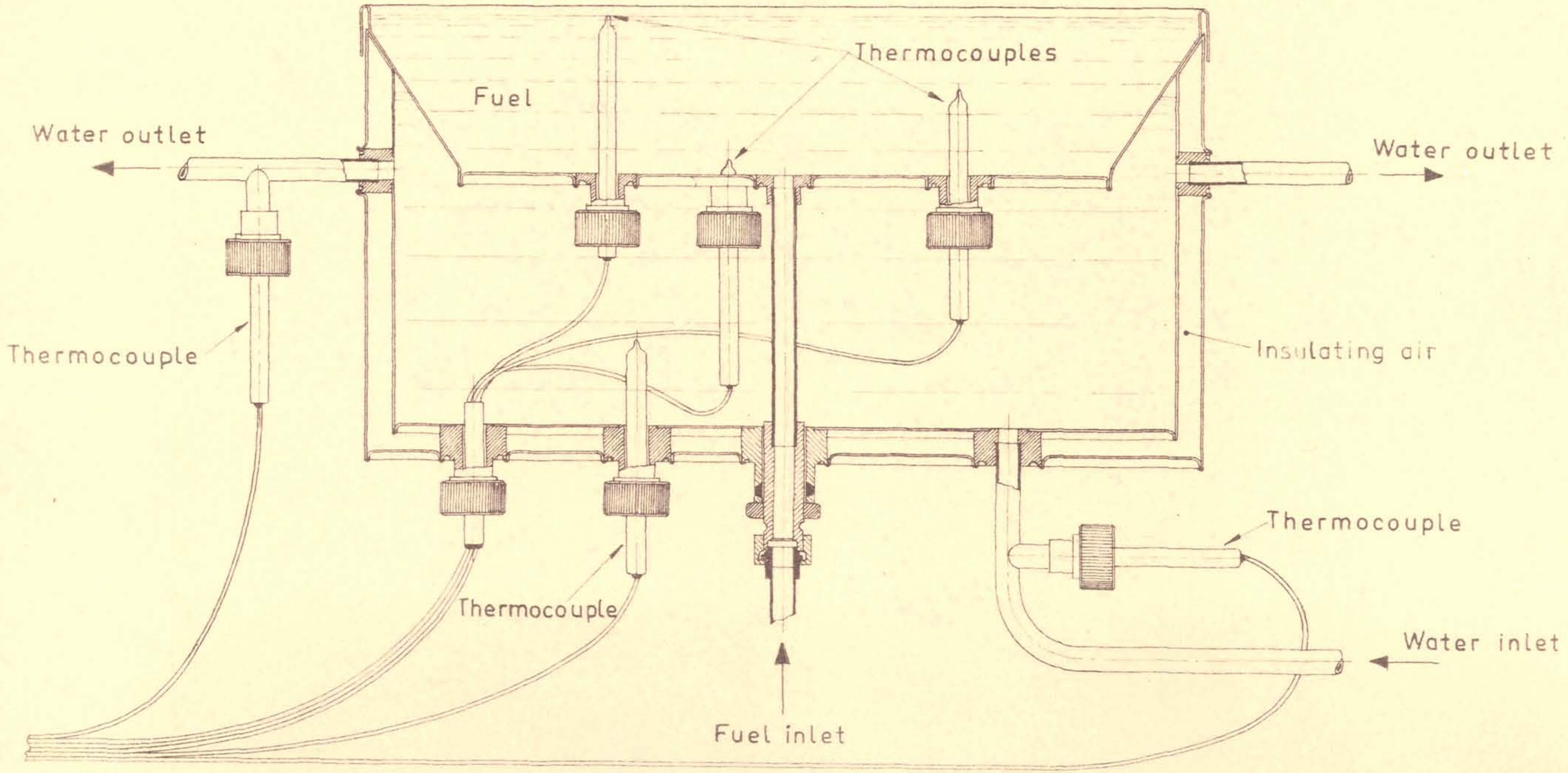


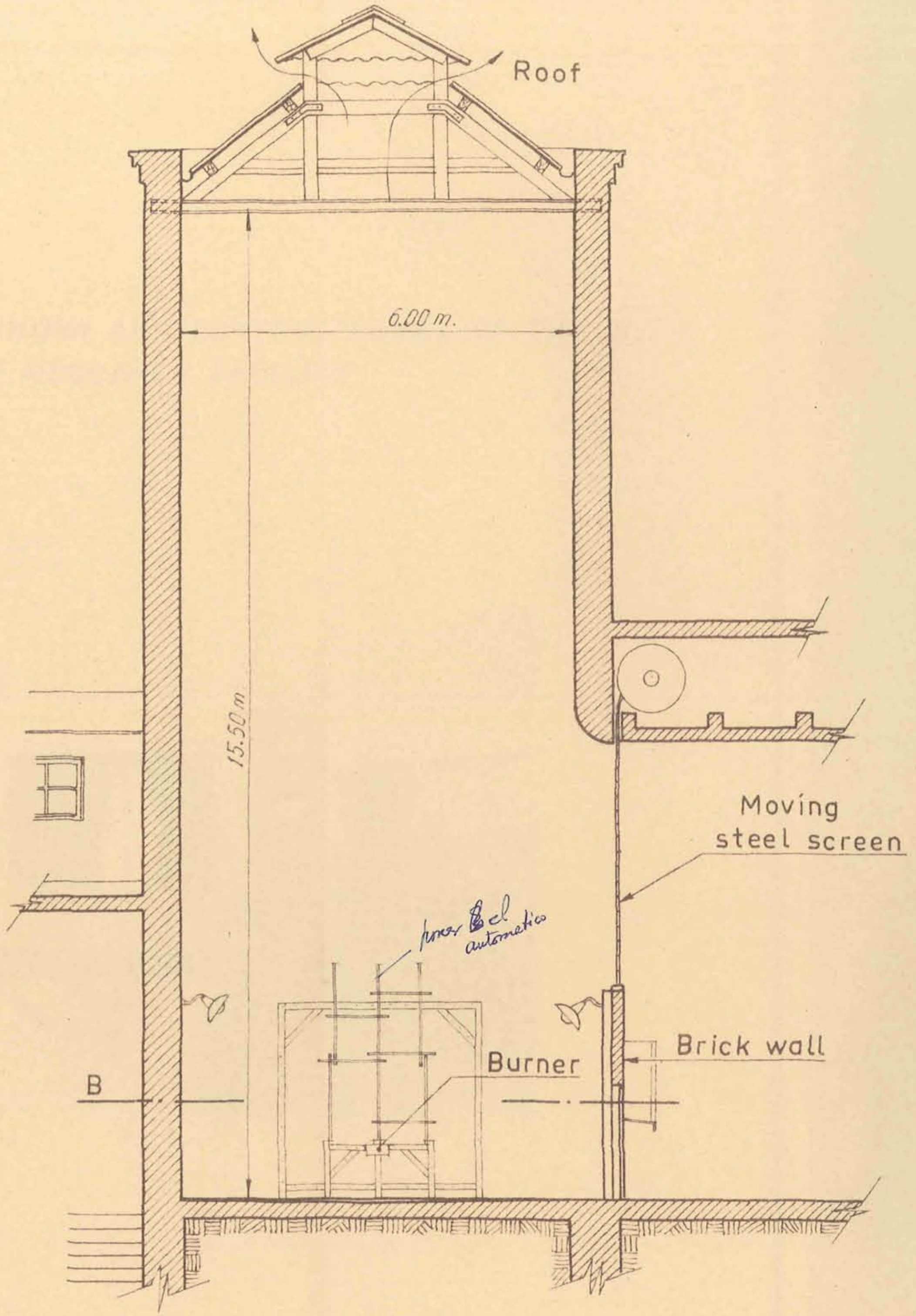
FIG. 4



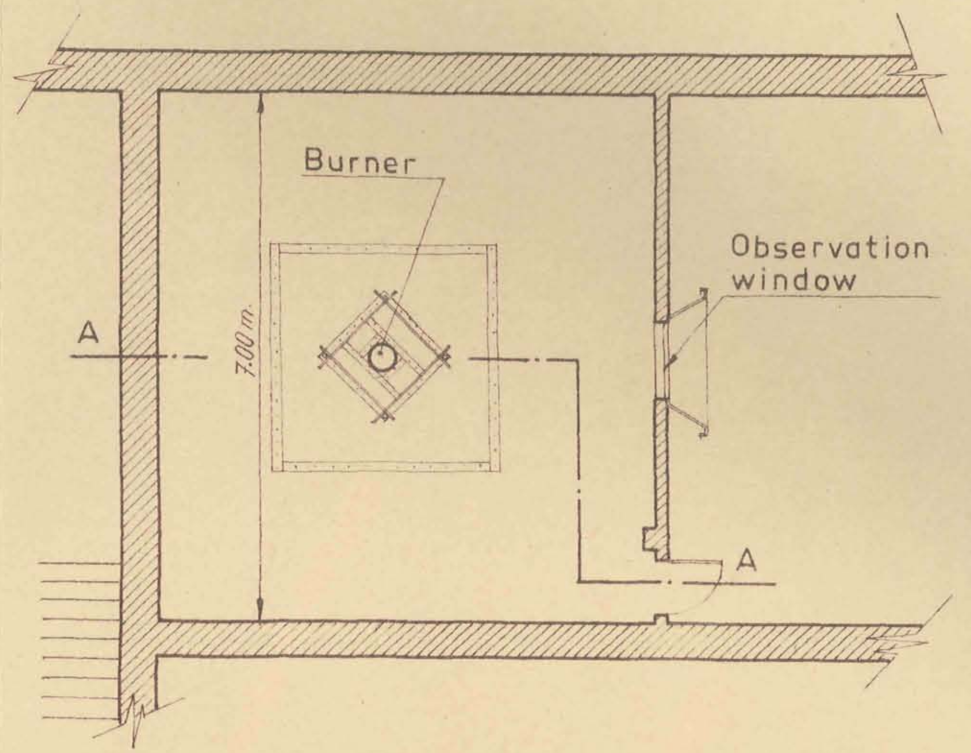
OPEN BURNER FOR STUDYING LIQUID FIRES

FIG. 5

FIG. 6



A-A SECTION

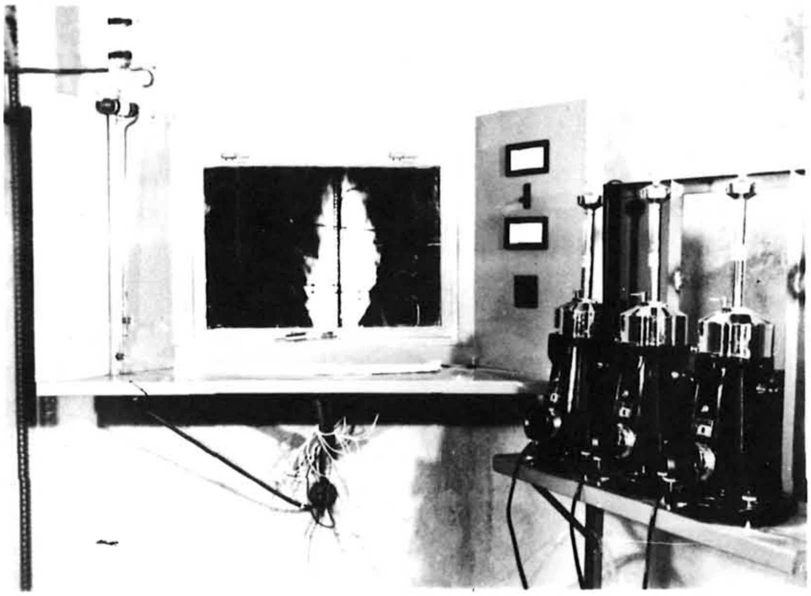


B-B SECTION

TEST STAND PREPARED FOR STUDYING LIQUID FIRES

FIG. 7

OBSERVATION WINDOW AND CONTROL PANEL OF THE OPEN FIRE RESEARCH FACILITY



BURNING RATES

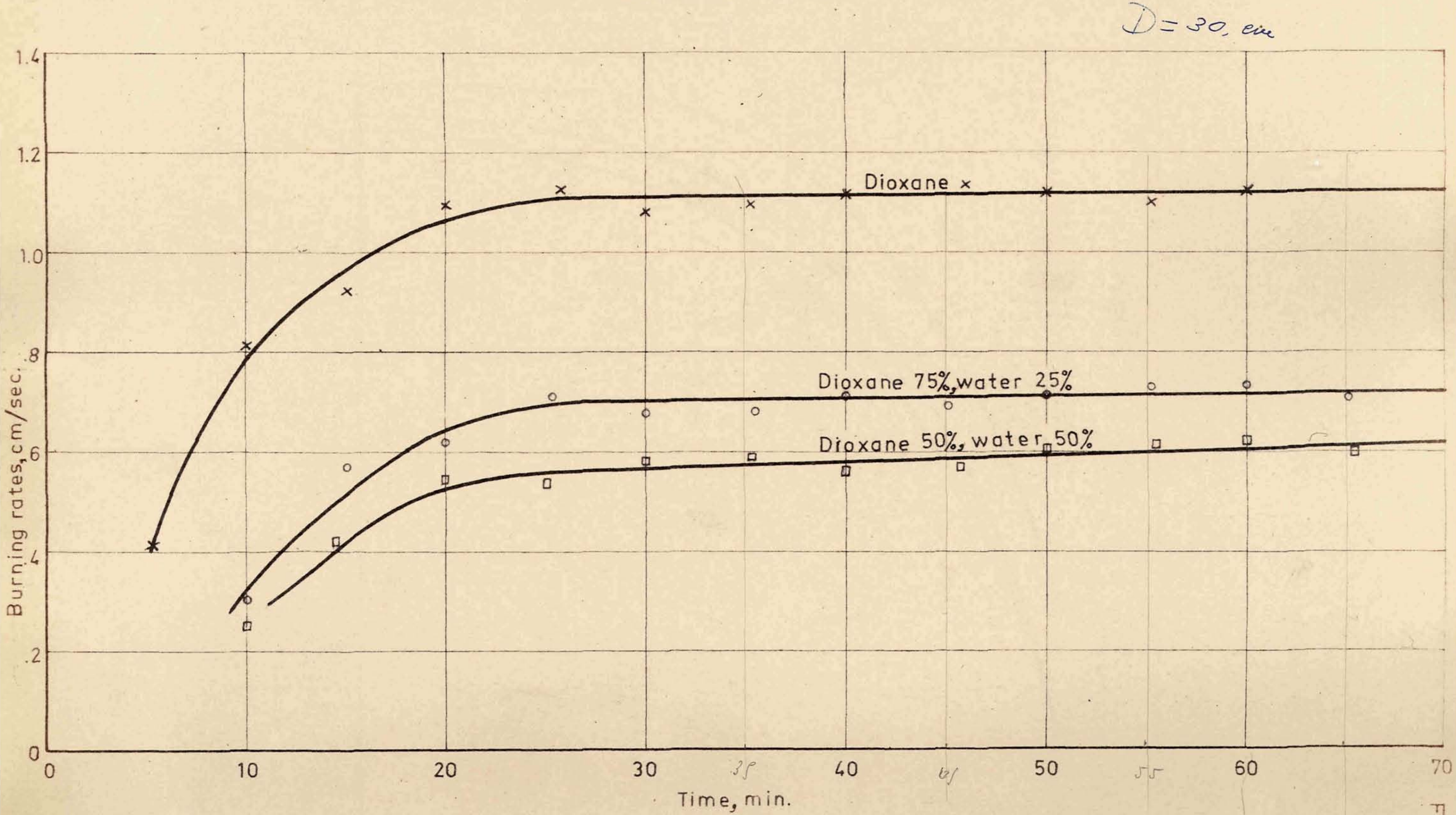
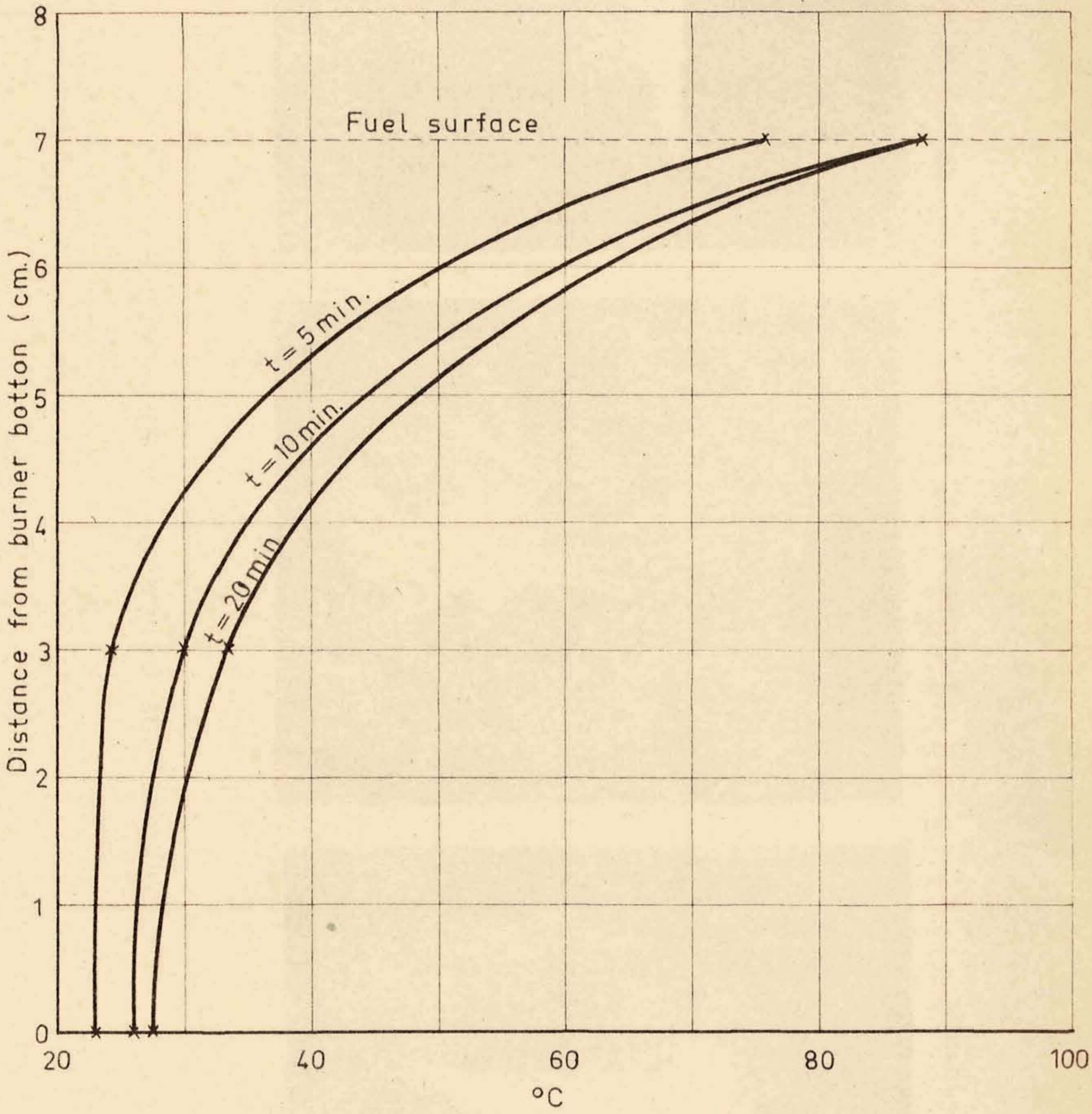


FIG. 8

FIG. 9.

FUEL TEMPERATURE DISTRIBUTION

(Dioxane)



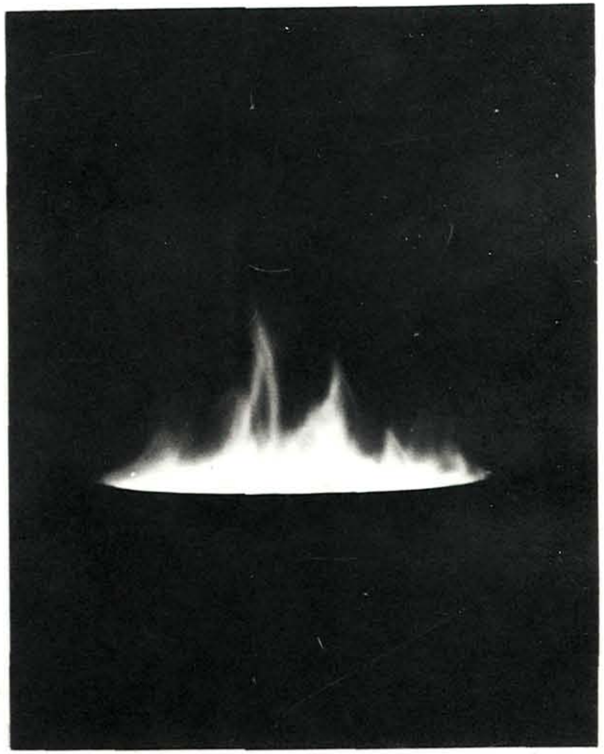
D= 30 cm

Mísma Escala

FLAMES OF DIOXANE-WATER MIXTURES

100% Dioxane

75% Dioxane, 25% water

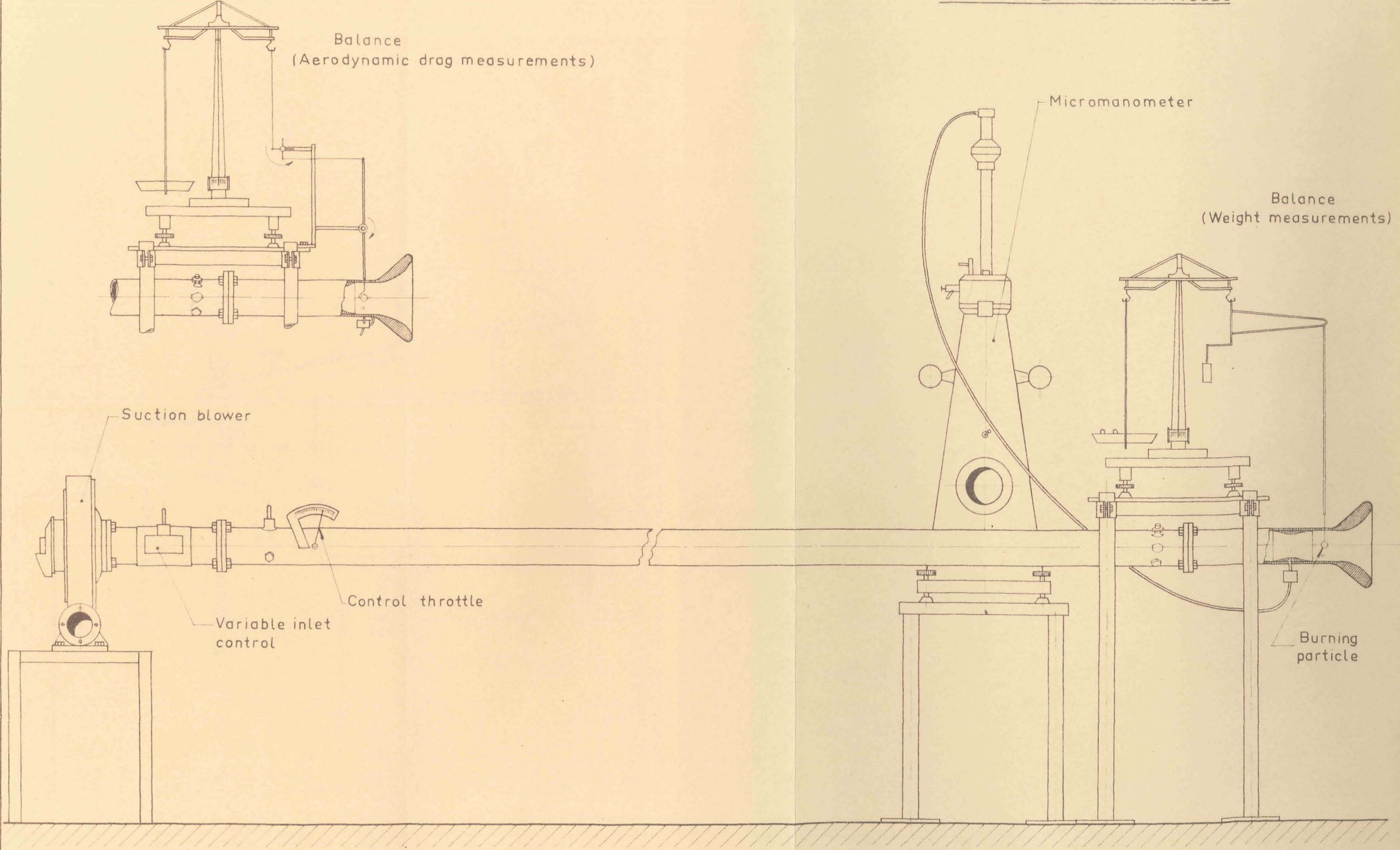


50% Dioxane, 50% water

FIG. 10

FIG 11

SMALL SUCTION WIND TUNNEL FOR MEASURING DRAG AND WEIGHT OF BURNING PARTICLES



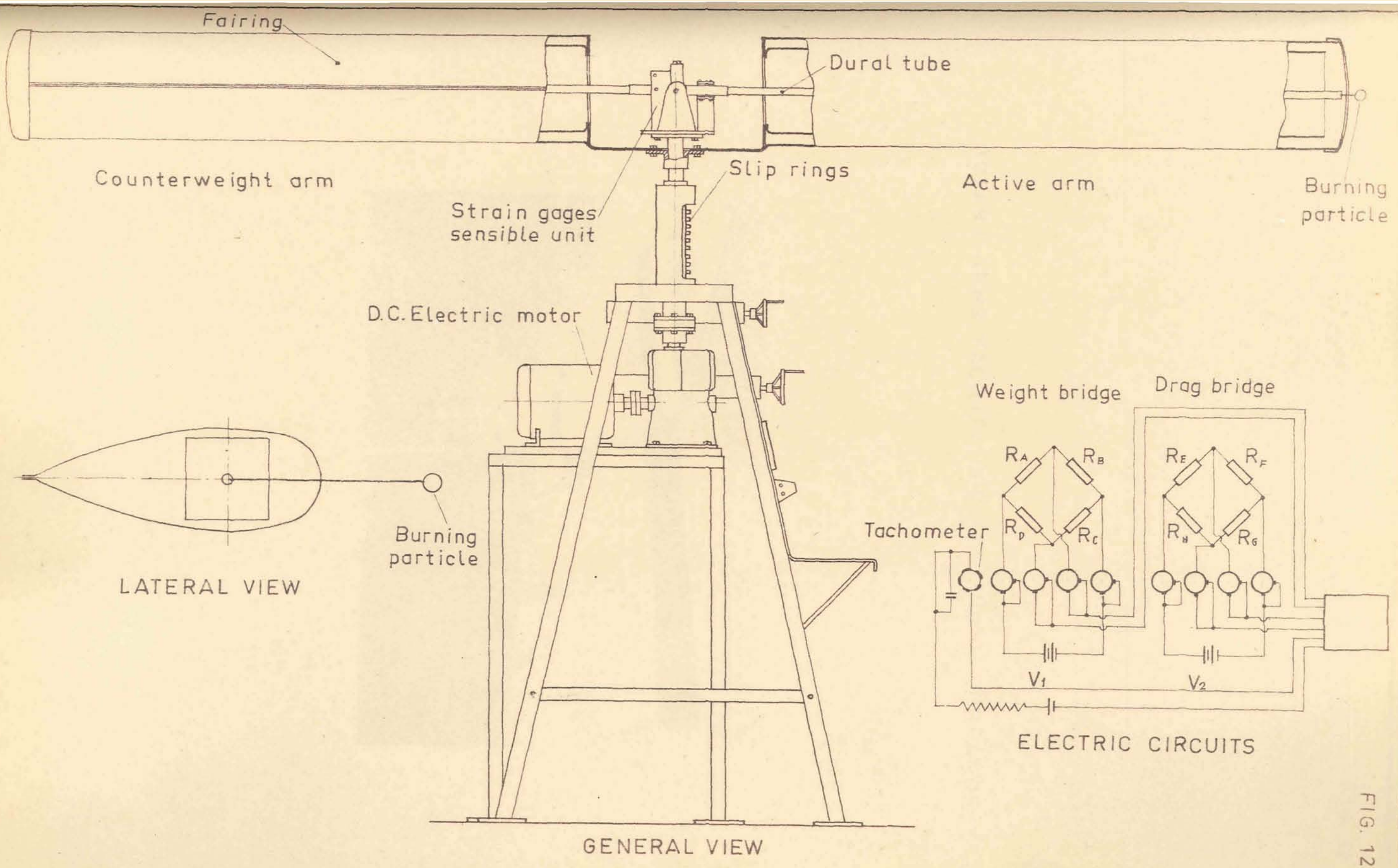
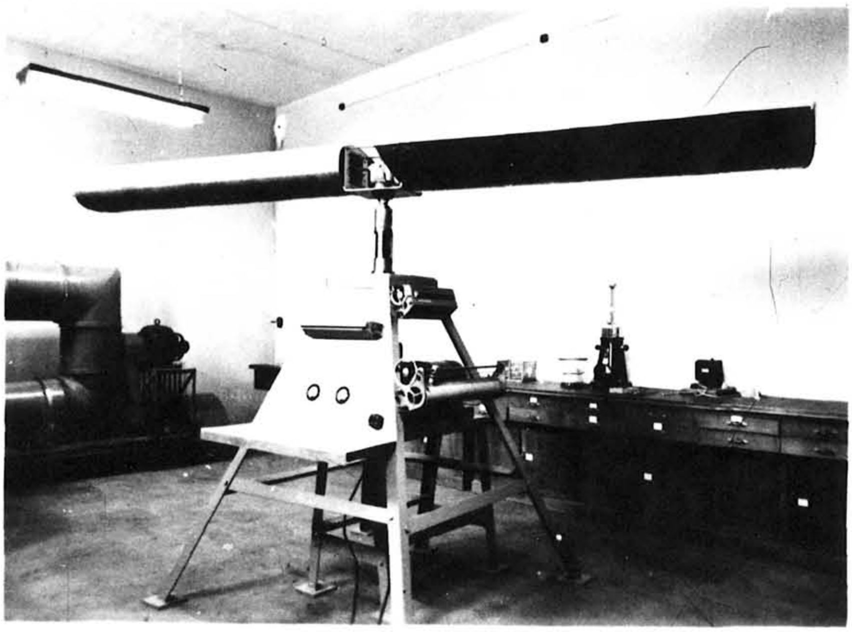


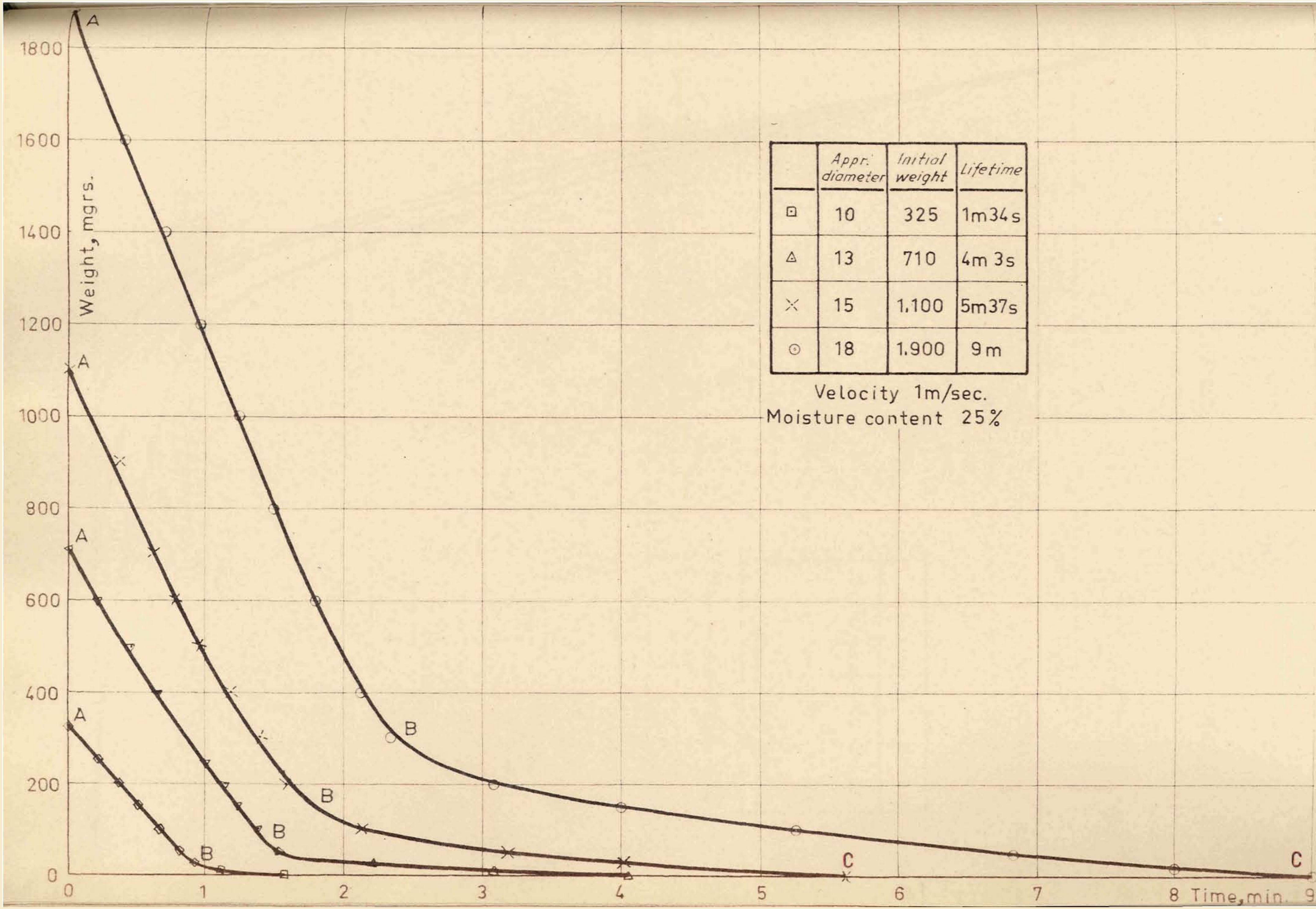
FIG. 12

ROTATING ARMS RESEARCH FACILITY FOR MEASURING THE DRAG AND WEIGHT OF BURNING PARTICLES

FIG. 13

ROTARY ARMS FACILITY FOR TESTING FIREBRANDS

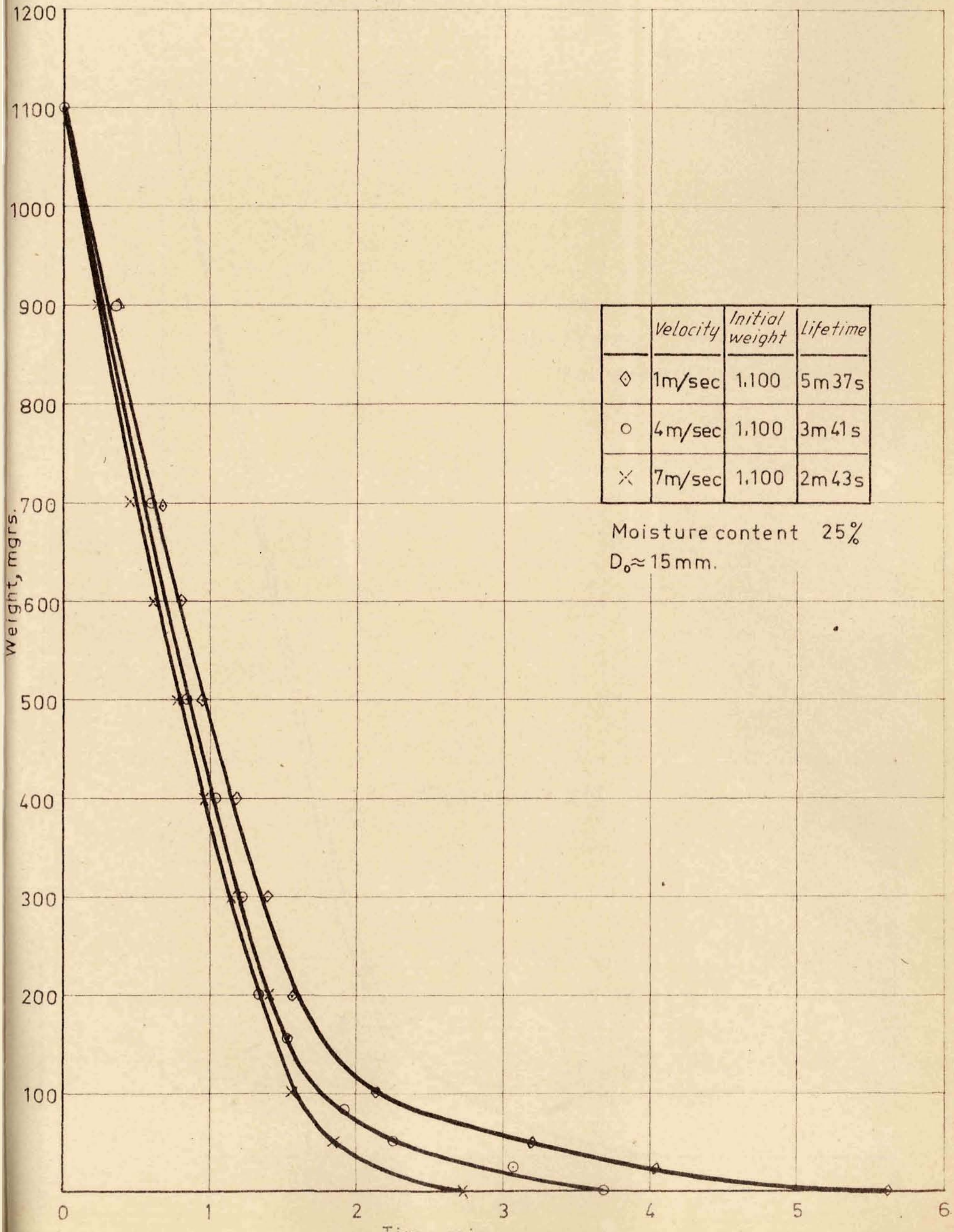




Weight, mgrs.
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8 Time, min. 9
A
A
A
A
B
B
B
B
C
C
Appr. diameter
Initial weight
Lifetime
10
325
1m34s
13
710
4m 3s
15
1.100
5m37s
18
1.900
9m
Velocity 1m/sec.
Moisture content 25%

FIG. 14

FIG. 15

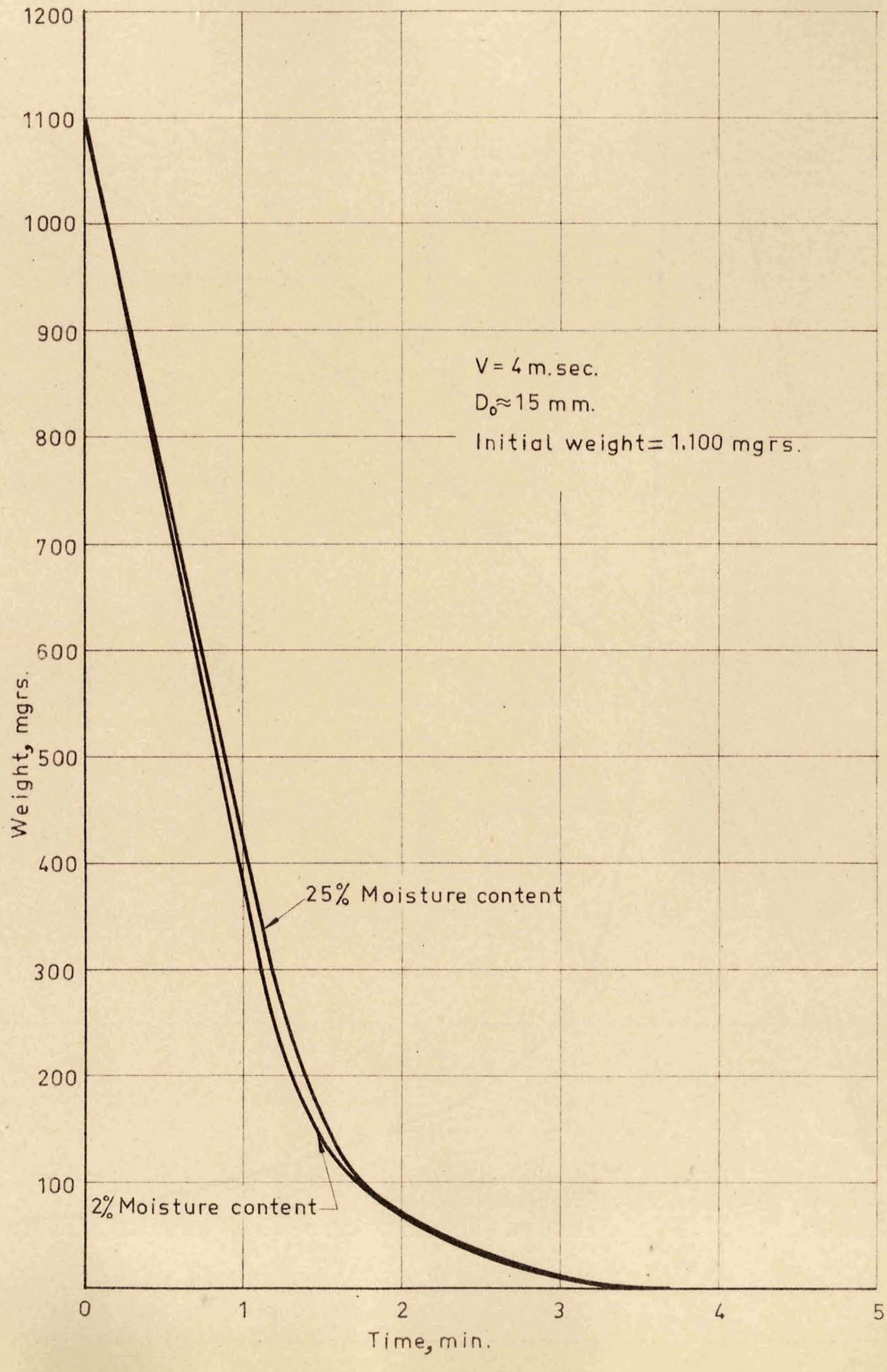


	Velocity	Initial weight	Lifetime
◊	1m/sec	1.100	5m 37s
○	4m/sec	1.100	3m 41s
×	7m/sec	1.100	2m 43s

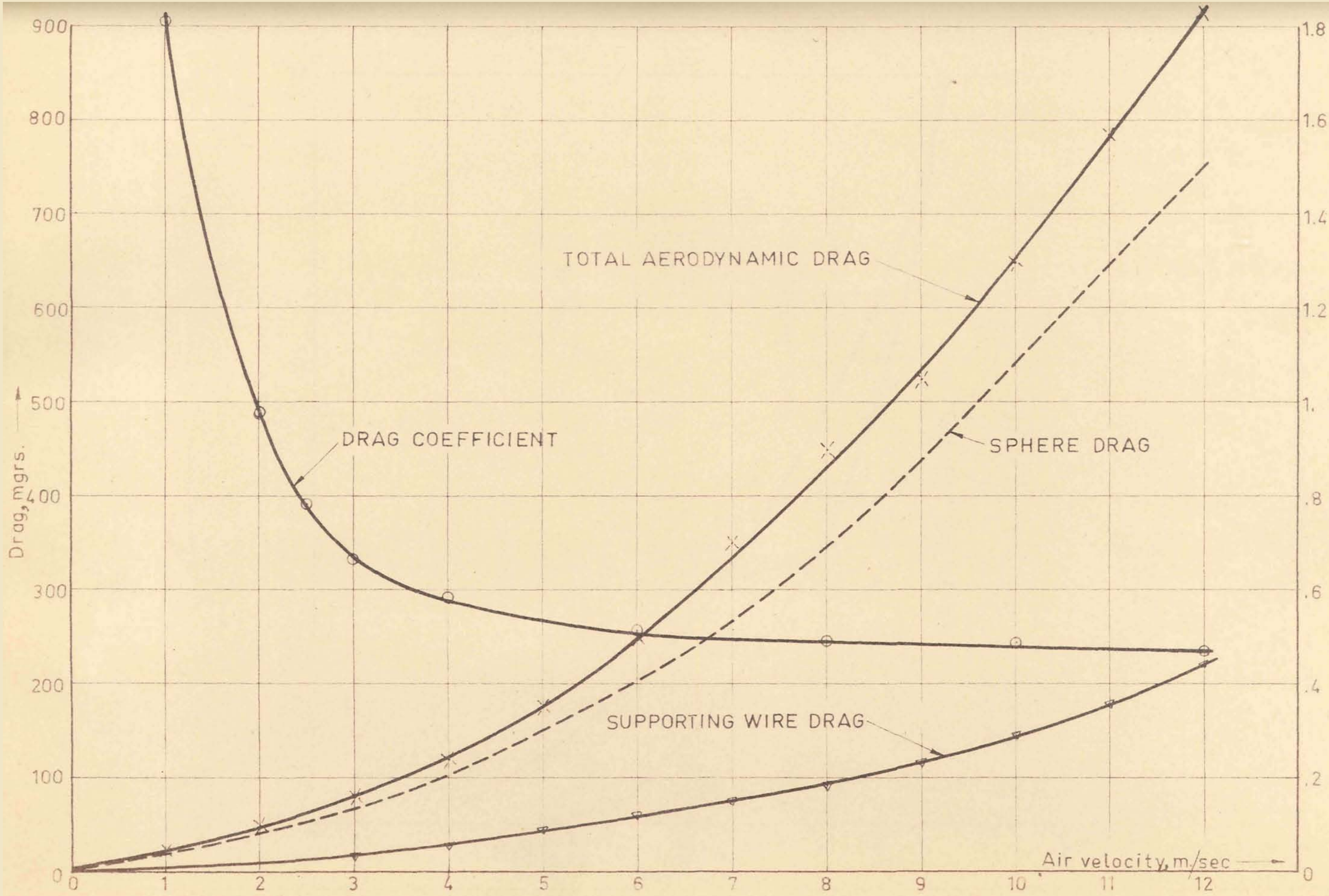
Moisture content 25%

$D_0 \approx 15$ mm.

FIG. 16



V = 4 m.sec.
$D_0 \approx 15$ mm.
Initial weight = 1.100 mgrs.
25% Moisture content
2% Moisture content
Weight, mgrs.
Time, min.
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5



TOTAL AERODYNAMIC DRAG
SPHERE DRAG
DRAG COEFFICIENT
SUPPORTING WIRE DRAG
Drag, mgrs.
Drag coefficient
Air velocity, m/sec
0
100
200
300
400
500
600
700
800
900
.2
.4
.6
.8
1.
1.2
1.4
1.6
1.8
1
2
3
4
5
6
7
8
9
10
11
12

FIG. 17

FIG. 18

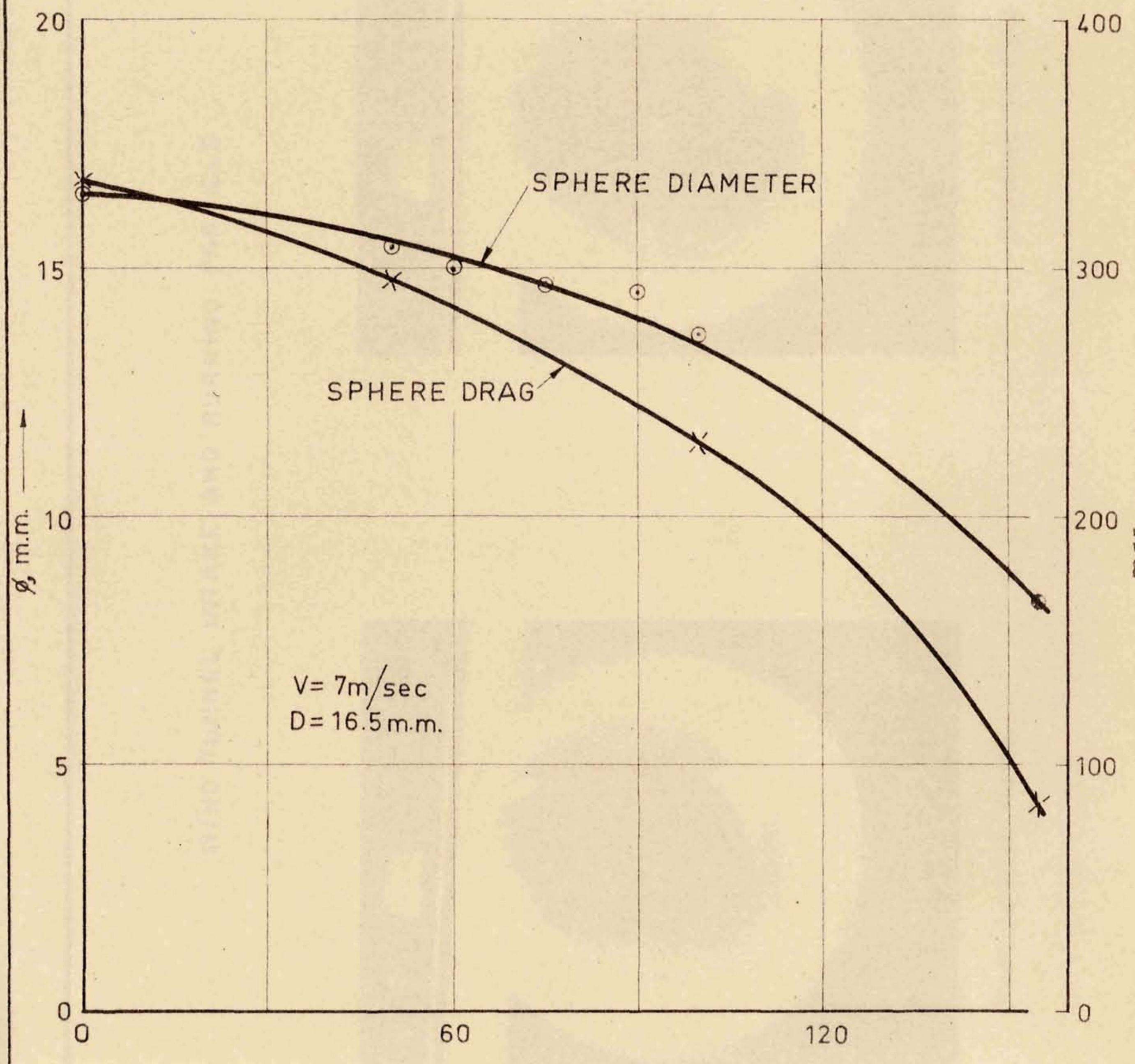
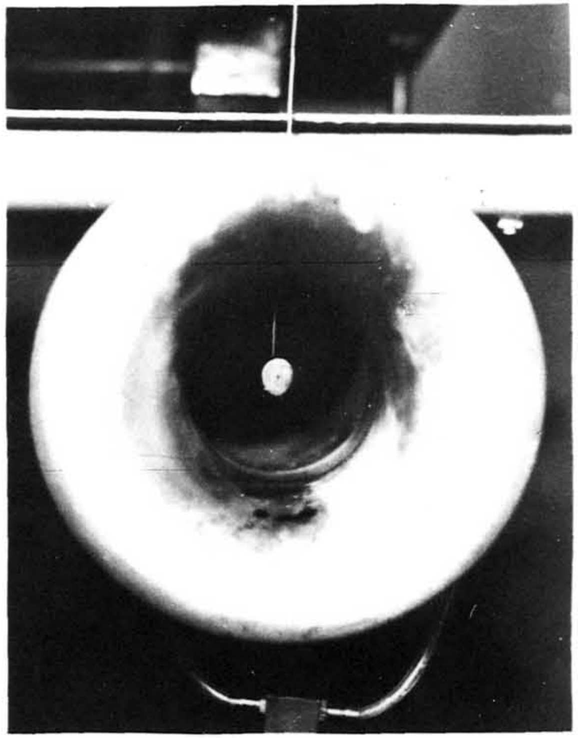

SPHERE DIAMETER
SPHERE DRAG
V= 7m/sec
D= 16.5 m.m.
ø, m.m.
mgr.
Time, sec.
20
15
10
5
0
400
300
200
100
0
0
60
120

FIG. 19

WIND TUNNEL INTAKE AND BURNING PARTICLE

Particle with flame



Glowing particle

FIG. 20

SCHEMATIC WIND CONDITIONS

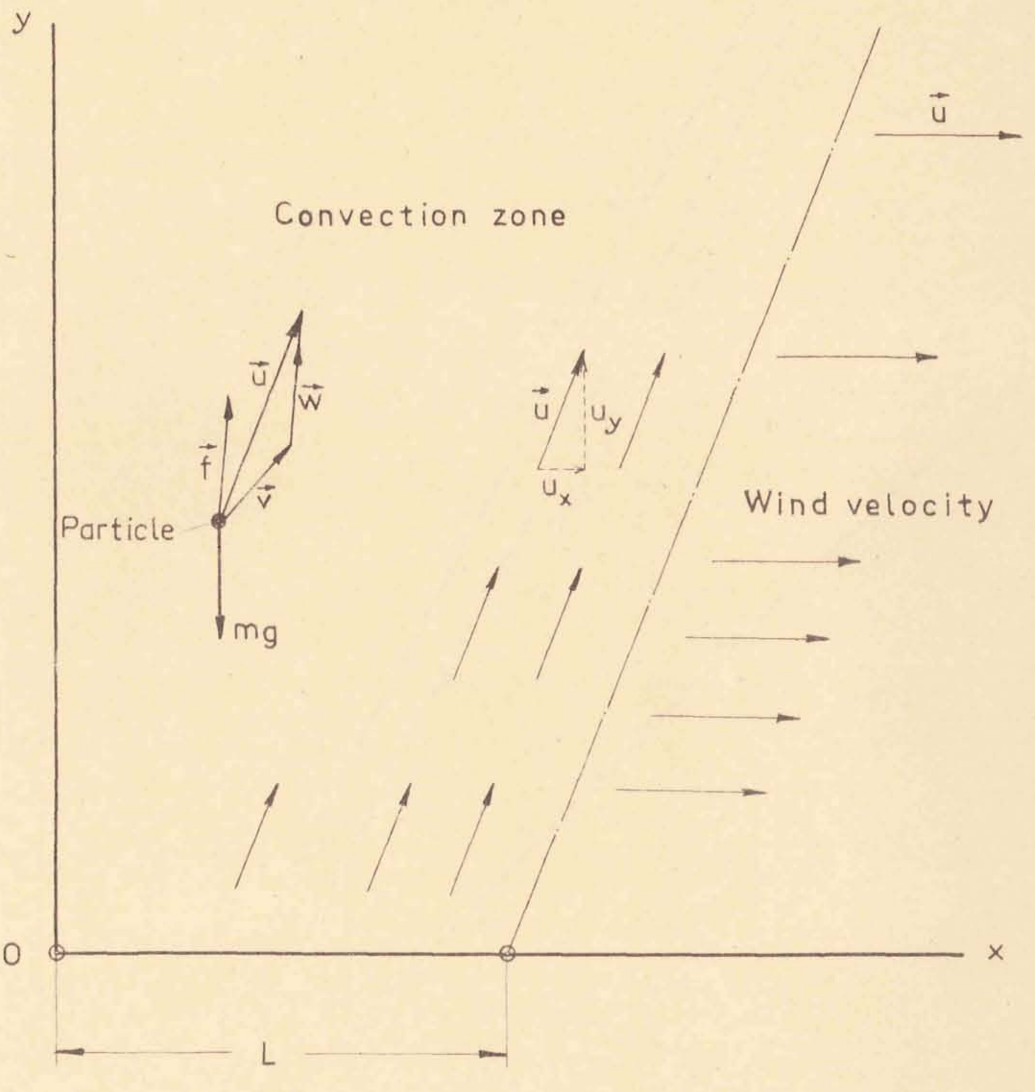


FIG. 21

INITIAL PART OF THE SPHERICAL FIREBRAND FLY PATHS

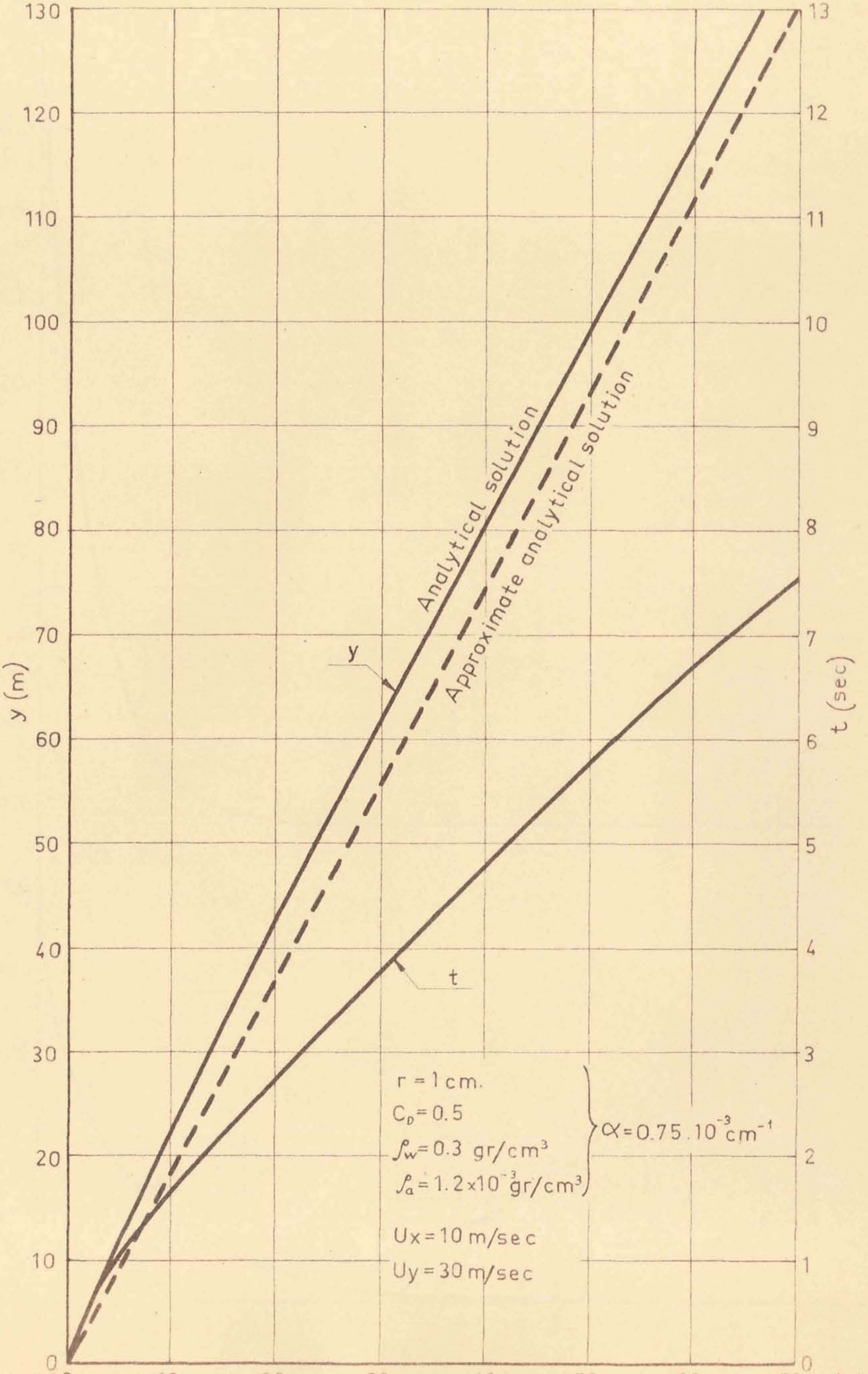
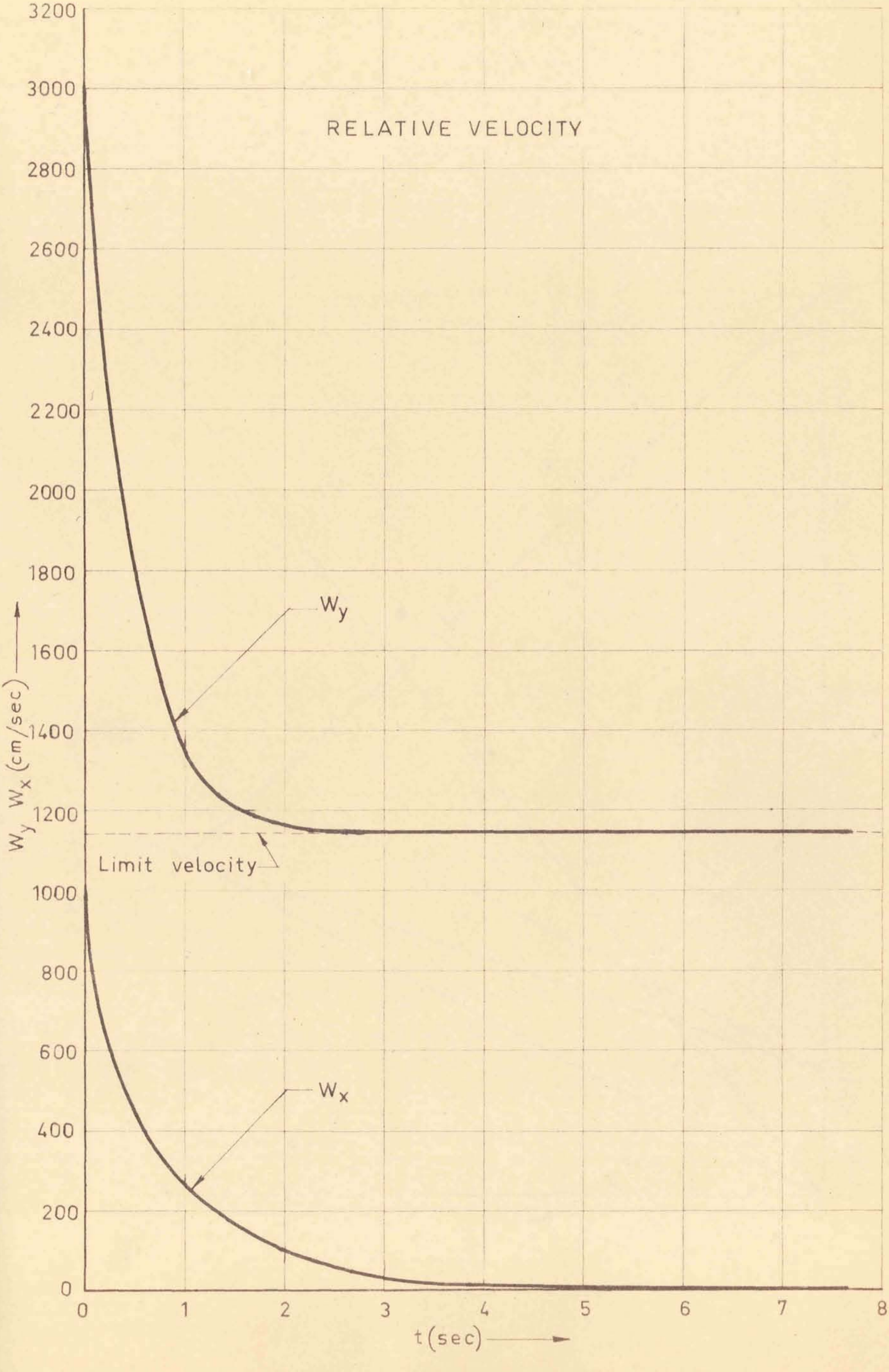


FIG. 22


RELATIVE VELOCITY
W_y
W_x
Limit velocity
W_y W_x (cm/sec)
t(sec)
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8

APPROXIMATE ANALYTICAL FLY PATHS

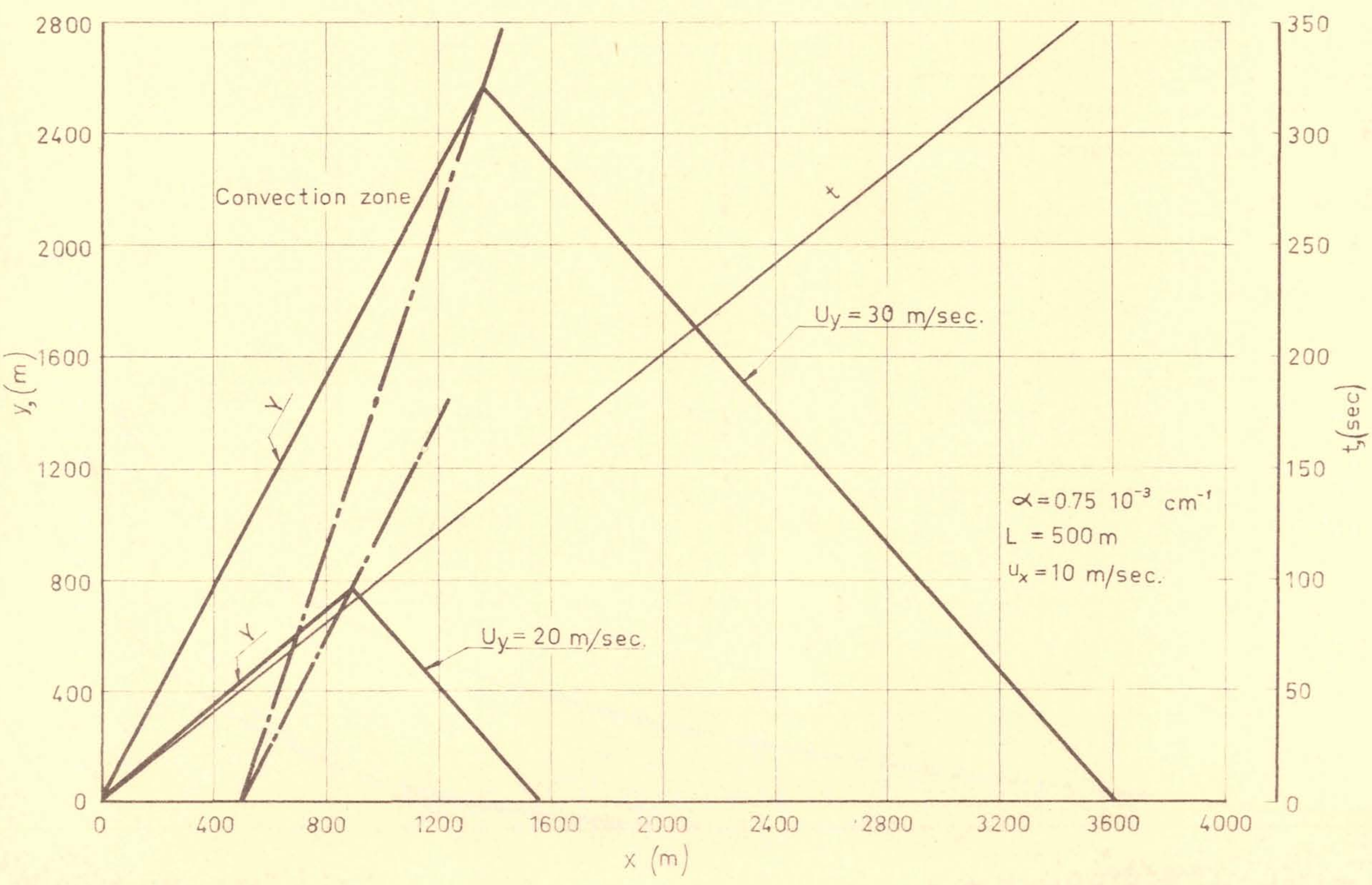


FIG. 23

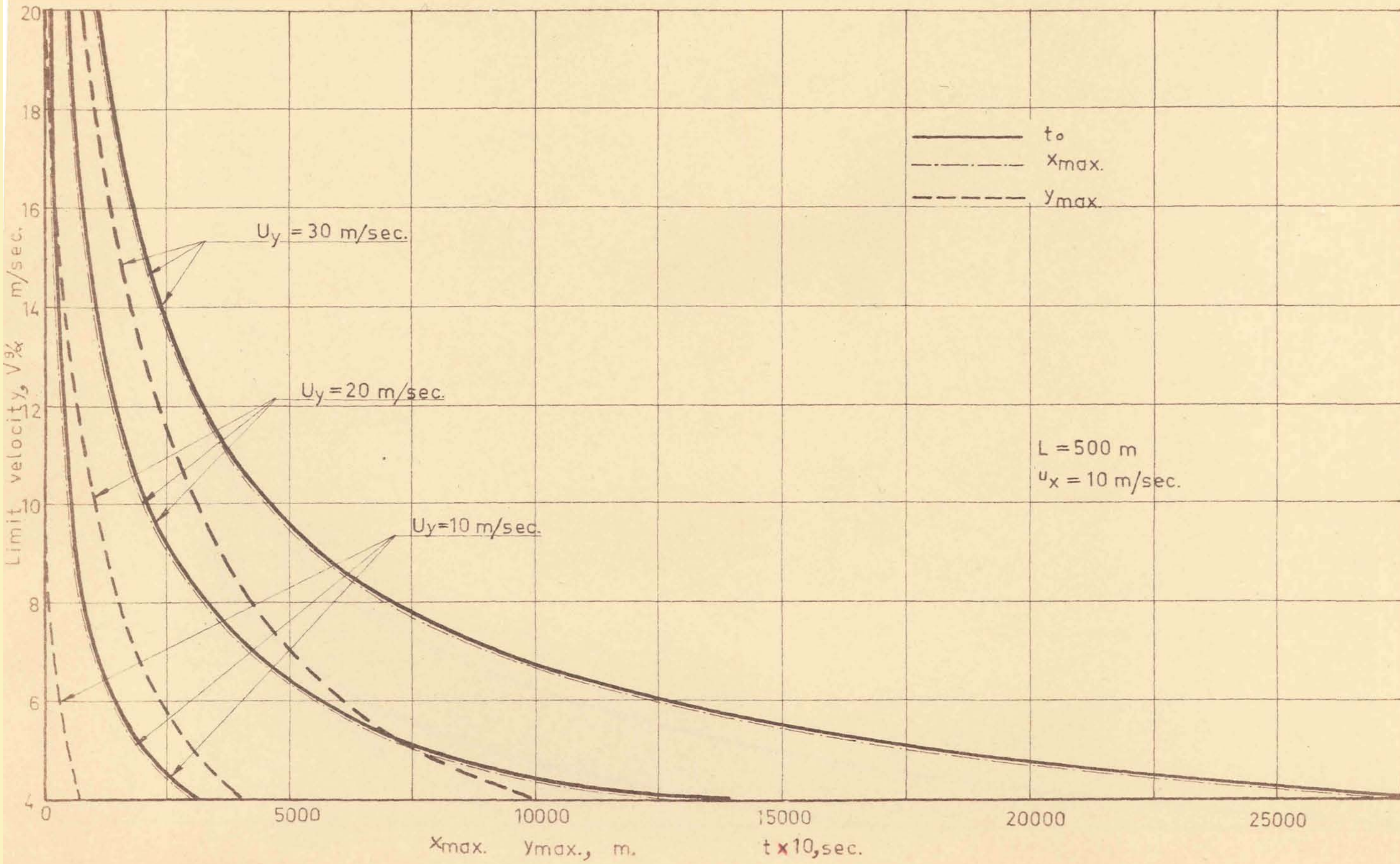
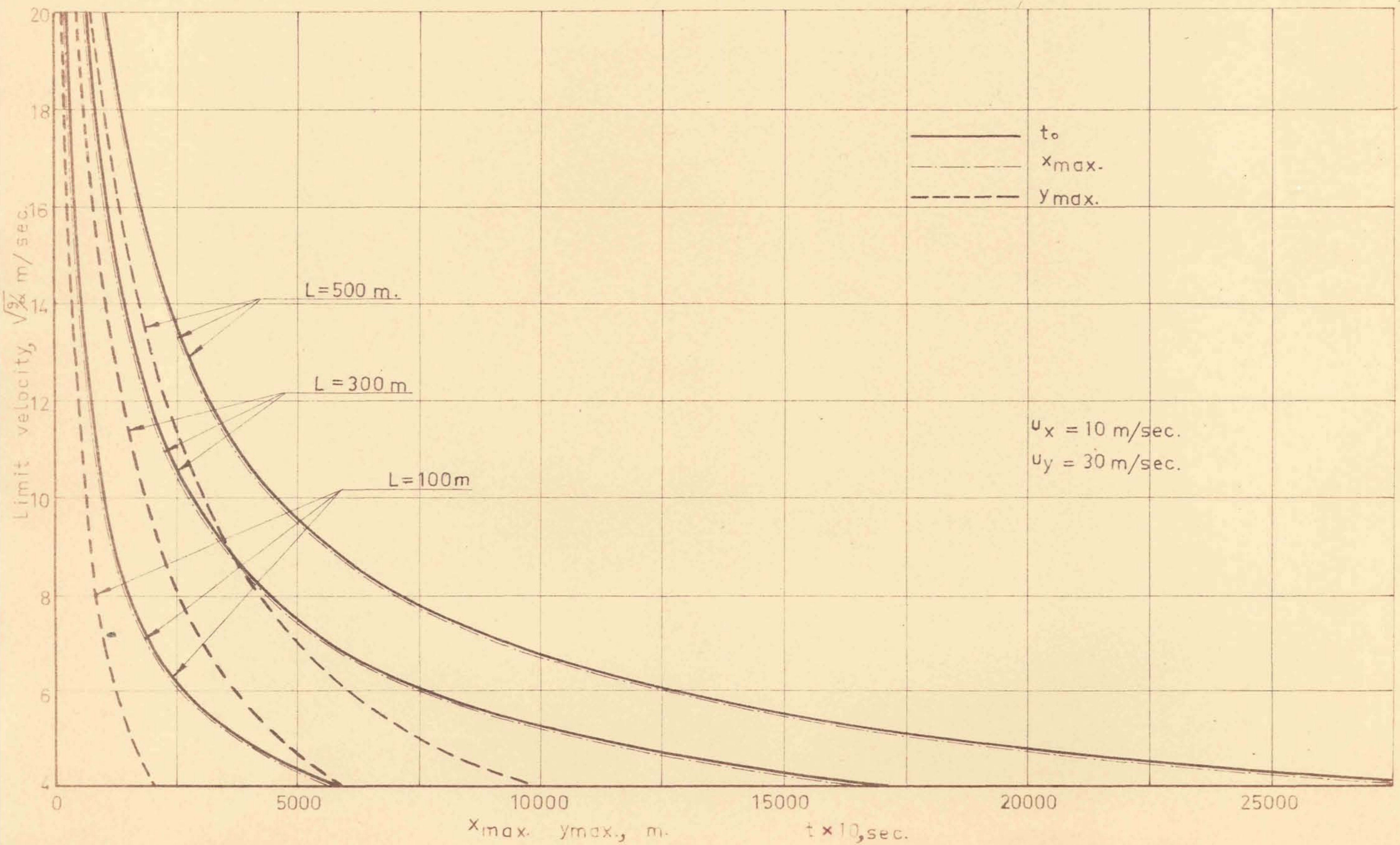

t₀
$x_{max.}$
$y_{max.}$
$U_y = 30$ m/sec.
$U_y = 20$ m/sec.
$U_y = 10$ m/sec.
L = 500 m
$u_x = 10$ m/sec.
Limit velocity, $V\frac{g}{\alpha}$ m/sec.
20
18
16
14
12
10
8
6
4
0
5000
10000
15000
20000
25000
$x_{max.}$ $y_{max.}$, m. t x 10, sec.

FIG. 24



20
18
16
14
12
10
8
6
4
Limit velocity, $\sqrt{g/\alpha}$ m/sec.
0
5000
10000
15000
20000
25000
x_{max}, y_{max}, m. $t \times 10$, sec.
t_o
x_{max}.
y_{max}.
L = 500 m.
L = 300 m
L = 100m
$u_x = 10$ m/sec.
$u_y = 30$ m/sec.

FIG. 25